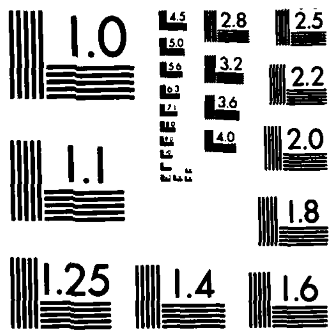
AD-A160 750 A MODEL FOR EVALUATING COMMUNICATIONS SATELLITE INTEROPERABILITY(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH T C GILL 1985 1/2

UNCLASSIFIED AFIT/CI/NR-85-103T F/G 22/2 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

UNCLASS

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFIT/CI/NR 85- 103T	2. GOVT ACCESSION NO. AD-A160750	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A Model for Evaluating Communications Satellite Interoperability		5. TYPE OF REPORT & PERIOD COVERED THESIS/~~DISSERTATION~~
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Timothy Curtis Gill		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS AFIT STUDENT AT: University of Colorado		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS AFIT/NR WPAFB OH 45433 - 6583		12. REPORT DATE 1985
		13. NUMBER OF PAGES 120
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASS
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES APPROVED FOR PUBLIC RELEASE: IAW AFR 190-1		Lynn Wolaver LYNN E. WOLAVER 3 Oct 85 Dean for Research and Professional Development AFIT, Wright-Patterson AFB OH
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) ATTACHED		

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASS

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Gill, Timothy Curtis (M.S., Telecommunications)
Trapp, Robert Leigh (M.S., Telecommunications)

A Model for Evaluating Communications Satellite Interoperability

Thesis directed by Professor Frank S. Barnes

This project describes a model with which emergency communications planners can evaluate the potential interoperability of satellite systems. Based on minimum communications requirements set forth by the Commercial Satellite Survivability Task Force of the National Telecommunications Advisory Committee, the model addresses the technical considerations involved in system interoperability and provides the basis for further study.

This paper addresses the need for finding techniques to implement an interoperable network of commercial satellites to augment our national security/emergency preparedness communications. Commercial satellite networks play an increasingly important role in providing essential communications during peacetime. They offer the means to quickly restore damaged or destroyed communications to isolated parts of the country during times of national security stress. However, the use of different technical methods by system operators presents major roadblocks to network interoperability.

Satellite communications would play a significant role in preventing a nuclear exchange if a crisis arose and would be important assets to our strategic forces if prevention were to fail. No single communications system is robust enough to withstand a direct

attack. Therefore, it is necessary to take advantage of the capabilities afforded by combining the assets of existing and planned commercial satellite systems. The problem of combining these resources is the subject of this project.

AFIT RESEARCH ASSESSMENT

The purpose of this questionnaire is to ascertain the value and/or contribution of research accomplished by students or faculty of the Air Force Institute of Technology (AU). It would be greatly appreciated if you would complete the following questionnaire and return it to:

AFIT/NR
Wright-Patterson AFB OH 45433

RESEARCH TITLE: A Model for Evaluating Communications Satellite Interoperability

AUTHOR: Timothy Curtis Gill

RESEARCH ASSESSMENT QUESTIONS:

1. Did this research contribute to a current Air Force project?

( ) a. YES ( ) b. NO

2. Do you believe this research topic is significant enough that it would have been researched (or contracted) by your organization or another agency if AFIT had not?

( ) a. YES ( ) b. NO

3. The benefits of AFIT research can often be expressed by the equivalent value that your agency achieved/received by virtue of AFIT performing the research. Can you estimate what this research would have cost if it had been accomplished under contract or if it had been done in-house in terms of manpower and/or dollars?

( ) a. MAN-YEARS ________ ( ) b. $________

4. Often it is not possible to attach equivalent dollar values to research, although the results of the research may, in fact, be important. Whether or not you were able to establish an equivalent value for this research (3. above), what is your estimate of its significance?

( ) a. HIGHLY SIGNIFICANT ( ) b. SIGNIFICANT ( ) c. SLIGHTLY SIGNIFICANT ( ) d. OF NO SIGNIFICANCE

5. AFIT welcomes any further comments you may have on the above questions, or any additional details concerning the current application, future potential, or other value of this research. Please use the bottom part of this questionnaire for your statement(s).

NAME GRADE POSITION

ORGANIZATION LOCATION

STATEMENT(s):

D

103

A MODEL FOR EVALUATING COMMUNICATIONS SATELLITE INTEROPERABILITY

by

Timothy Curtis Gill

B.A., Johnson State College, 1975

and

Robert Leigh Trapp

B.S., Miami University, 1977

A project submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirements for the degree of

Master of Science

Program in Telecommunications

1985

This Project for the Master of Science Degree by

Timothy Curtis Gill

and

Robert Leigh Trapp

has been approved for the

Program in Telecommunications

by

Frank S. Barnes

Dale N. Hatfield

S. W. Maley

Date 7/30/85

CONTENTS

CONTENTS (continued)

CONTENTS (continued)

TABLES

Table

FIGURES

DISCLAIMER

The opinions expressed are those of the authors, and do not necessarily reflect the views of the United States Air Force, the Department of Defense, or any other government agency. No classified material was used in the production of this project. Review of this project by Department of Defense personnel does not necessarily constitute an endorsement.

CHAPTER I

INTRODUCTION

Under normal circumstances, providers of domestic satellite service in the United States need not be concerned with the question of whether or not their systems will operate effectively with those of other carriers. However, the U.S. government relies heavily on these private sector providers for its routine telecommunications needs and will look to them even more in times of a national emergency. Such an emergency could easily destroy significant portions of the telecommunications assets normally used to supply communications for the federal government. In such an event, the government would have to look to the remaining assets of the private sector carriers to supply minimum essential emergency communications. Because of their coverage of the United States, satellite communications systems would appear to offer the most flexible means of establishing connections to emergency locations.

Depending on the nature of the emergency, there may be no significant interruption of communications services. But in the event of a severe emergency such as a nuclear attack or catastrophic natural disaster (major earthquake, hurricane, etc.), the routine communications assets may no longer be operable. Assets from previously separate systems would need to be connected in such a way as to provide the necessary emergency communications.

The NSTAC Process

The basis for joint planning between government and industry can be found in Presidential Directive 53 (PD-53), National Security Telecommunications Policy, which points out the importance of common carrier networks to national security. Recognizing the dependence on the commercial networks for providing critical government telecommunications needs, in 1981 the National Security Council directed the National Communications System (NCS) to assess the vulnerability of the U.S. commercial telecommunications systems and to develop initiatives to improve the identified problems. Areas initially identified were the need for a framework for government and industry joint planning, improving the survivability of commercial satellite communications assets, and ensuring a survivable automated information processing capability to support national decision makers. NSTAC was formed to obtain industry advice and include industry in the process of examining solutions to the problems described above.[1]

The National Security Telecommunications Advisory Committee (NSTAC) was established by Executive Order 12382 to provide industry advice and expertise on enhancing the survivability of commercial telecommunications systems which support national security and emergency preparedness requirements. As a Presidential advisory committee, the NSTAC enables the U.S. federal government to draw upon the expertise of the telecommunications industry to address major survivability issues. The committee provides the basis for joint planning

by industry and government on such issues and indicates the federal government's recognition that it must work in partnership with the private industry that builds, owns, and operates the nation's telecommunications networks. The creation of NSTAC further demonstrates the government's commitment to establishing partnerships with industry to achieve national goals.[2]

The NSTAC was established when President Reagan appointed chief executive officers from the telecommunications, satellite manufacturing, and information processing industries. These members appointed an Industry Executive Subcommittee (IES) to conduct issue-oriented meetings at a working level, using additional working groups and task forces as necessary to address specific issues and initiatives. The IES also serves as the steering group for the overall NSTAC effort. It currently coordinates the efforts of three subordinate groups: Resource Enhancement, Emergency Response Procedures, and Funding and Regulatory. These groups perform detailed analyses, formulate options, and prepare recommendations for the NSTAC.[3]

At their first formal meeting on December 14, 1982, the NSTAC agreed to emphasize commercial satellite communication survivability initiatives as a matter of priority in addressing the overall telecommunications system survivability issue and to prepare a plan that recommends actions to be taken. During early government/industry meetings in 1982 to address satellite survivability, the government provided a series of briefings on the major threats to satellite communications, on vulnerabilities of the satellite systems, and on

possible courses of action that could be taken to address the weaknesses. Among the items presented were 30 initiatives which the government felt could be undertaken to improve survivability and robustness of commercial satellite communications resources. The industry representatives were asked to respond to the value of the various initiatives as well as to cost, schedule, and risk estimates. Although there was some concern from industry that some of the initiatives could impact upon the operability and profitability of the commercial resources, there was general agreement that the initiatives were technically feasible.[4]

The Resource Enhancements Working Group later formed the Commercial Satellite Survivability (CSS) Task Force to study issues which they subdivided into an "action set" and a "study set." On May 20, 1983, the task force issued a document titled Commercial Satellite Communications Survivability Report, providing their initial findings on the two sets of issues. An addendum to the report was released on December 15, 1983.

The CSS Task Force addressed a variety of issues in the two documents described in the preceding paragraph. These issues covered the entire range of subjects, both technical and non-technical, necessary to work towards an eventual contingency plan that would make use of a varied set of commercial satellite communications assets. The issues being investigated are contingency plans and emergency procedures; communications interoperability; communications security; control survivability; telemetry, tracking, and control (TT&C) inter-

operability; physical security; nuclear susceptibility and hardening; and funding and regulatory issues.

Scope of This Project

This paper builds a model for evaluating interoperability of U.S. domestic satellite systems in support of the commercial satellite survivability efforts described above. As part of the interoperability model, the minimum required communications capability will be defined and established as the benchmark for determining whether or not a given satellite link will provide the required level of service. Next, issues related to earth station location and the necessary elements of satellite link analysis will be presented to form the basis for the interoperability model. Other variables such as multiplexing, error coding, scrambling, modulation techniques, encryption, and access schemes will be addressed in terms of their basic characteristics and how they would affect satellite system interoperability. Due to the proprietary nature of earth station designs, specific earth station data will not be presented because they were not available to the authors. It is hoped that the material developed here will serve as a model for the appropriate government/industry entity to evaluate the interoperability of systems currently in use and those planned for the near future.

Because most of the new systems being deployed at the present time and planned in the near future operate in the Ku band (12/14 GHz), and because these systems are more diverse than the C-

band systems to be used in emergency situations, this paper will address itself directly to Ku-band systems. According to the Commercial Satellite Survivability (CSS) Task Force of the National Security Telecommunications Advisory Council (NSTAC), the Ku-band satellites offer the greatest concern in terms of interoperability. Although they are important concerns, the issues of contingency plans, communications security (beyond the interoperability issues), control survivability, physical security, and funding and regulatory issues will not be addressed in this project.

NOTES - CHAPTER I

[1] CSS Task Force. Commercial Satellite Communications Survivability Report, May 20, 1983, p. 1.

[2] Ibid., p. 2.

[3] Ibid.

[4] Ibid., p. 3.

CHAPTER II

THE INTEROPERABILITY MODEL

Interoperability Scenarios

Prior to developing the interoperability model, it is appropriate to define the different scenarios which may be encountered when trying to achieve two-way communications with assets from different satellite systems. In this way, levels of interoperability requirements can be established.

The first scenario, and probably the easiest to accommodate, is the situation where a particular satellite in one system is lost and two or more earth stations in the same system use a satellite from a different system to communicate. Since the network access is typically controlled from the ground and the satellite transponders are relatively transparent to the particular access scheme being used, this first option may involve little more than antenna pointing and frequency tuning.

The second scenario is somewhat more involved. In this case, two earth stations, each from a different system, use a satellite with which only one of them was designed to work. This means that the access method, coding, and other system-unique transmission equipment have to operate together. The third, and worst case, scenario is where two earth stations, not originally designed to operate

together, attempt to communicate by a third-party satellite. It should be noted, however, that the third case is only slightly more of a problem than the second since the satellite will be reasonably transparent to the operation. The three scenarios are depicted in Figure 2.1.

Interoperability Parameters

In their recommendations, the CSS Task Force suggested that a data base be established to assess the degree of compatibility between various earth stations and to determine the degree of usefulness in an emergency situation.[1] Their list of data elements is in Table 2.1. While the parameters are appropriate, the list leaves out several important variables. Error coding, scrambling and descrambling, and multiplexing techniques are the most obvious omissions.

In effect, there are two questions which must be answered to determine interoperability:

1. Can a signal of sufficient strength be relayed by a given satellite from one earth station to another?
2. Can the information in the relayed signal be intelligibly interpreted at the receiving earth station?

The first question can be addressed through examining earth station location (Chapter III) and link analysis (Chapter IV) and the second can only be answered in looking at earth station design in terms of the methods of signal conditioning and manipulation used prior to transmission (Chapters V-VII).

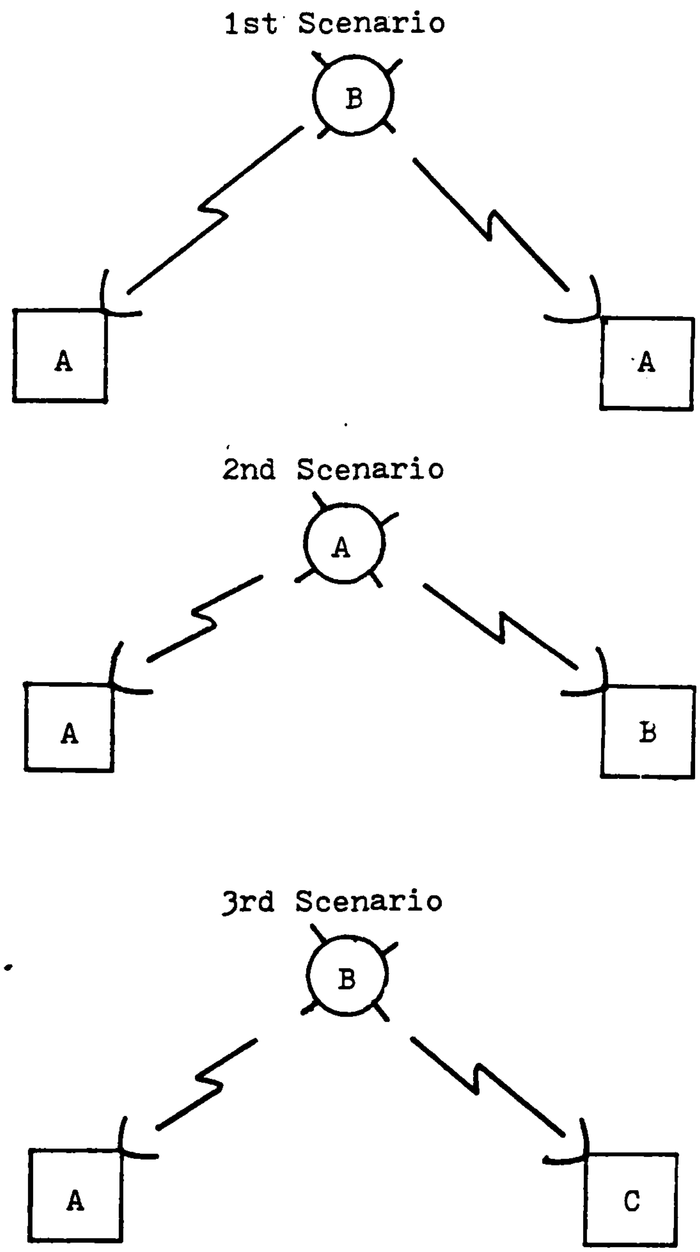


Figure 2.1. Interoperability Scenarios.

Table 2.1
CSS Task Force Compatibility Parameters

1. Geographical location
2. Customer premises or nodal point (address)
3. Amount of time manned
4. Emergency power capability
5. Earth station characteristics
    a. Antenna up/down converter
    b. Number of antennas at location
    c. Frequency agility
    d. Multiple carrier
    e. Polarization and adjustment capability
    f. Satellite tracking capability
    g. IF interface (frequency, signal level)
    h. Coverage of geosynchronous arc
    i. G/T
    j. EIRP/carrier
    k. Station application (video, voice, data, etc.)
    l. Modulation type (TDMA, FDMA, FM) and data rate
6. Network connectivity
7. Terrestrial connections

Minimum Required Capability

As recommended by the Resource Enhancements Working Group of the National Security Telecommunications Advisory Council, the minimum required communications capability would consist of at least a single DS-1 (1.544 Mbps) data channel and a single SCPC (single channel per carrier) voice channel.[2] In light of the capabilities of satellite systems in use today, this is a modest requirement. Current and planned satellite systems in the Ku-band carry transponders with bandwidths up to 72 MHz. However, the compability model should be based on the narrowest available bandwidth. At this time, the narrowest bandwidth transponder is 43 MHz deployed in the Satellite Business Systems (SBS) satellites.[3] By applying Shannon's Law, we can obtain the minimum required signal-to-noise ratio (SNR) required of the channel. That minimum SNR would provide the benchmark against which the link analyses would be evaluated. As presented by Martin, Shannon's Law is expressed as

$$C = W \log_2(1 + SNR)$$

where C rêpresents the channel capacity, W is the bandwidth of the channel, and SNR is the signal-to-noise ratio.[4] In the case of the DS-1 channel on a Ku-band satellite, we get

$$1.544 \times 10^6 = 4.3 \times 10^7 \log_2(1 + SNR)$$

where the desired channel capacity is 1.544 Mbps and the bandwidth is 43 MHz. Solving for SNR, we get a value of 0.0252 or 0.11 dB. This

is the minimum acceptable SNR which the emergency configuration would have to provide. However, 1.544 Mbps would be the theoretical maximum at that SNR and the actual rate would fall somewhere short of that. A minimum SNR of 10 dB would produce a maximum rate of 149 Mbps and should adequately cover the 1.544 Mbps requirement. The resulting signal-to-noise density ratio, S/N_o, and the bit time (based on the data rate) determine the energy per bit/noise density ratio, E_b/N_o. For a given value of E_b/N_o, the maximum bit error rate (BER) that can be achieved is determined by the modulation method used.[5]

Although the Commercial Satellite Survivability Report did not give precise requirements for the single channel per carrier (SCPC) capability, a general guideline can be established based on the likelihood that the required voice channel would be analog FM. The bandwidth for such a channel can be represented by

$$B = 2(m_f)(f)$$

where B is the bandwidth, m_f is the modulation index (typically in the range of 5 to 10), and f is the baseband bandwidth.[6] (Others, such as Gagliardi, express the modulation index as β in the expression $B = 2(\beta + 1)(f_m)$.[7] Given a 4 kHz voice signal, the required bandwidth, ignoring guard bands, would range from 40 kHz (with an FM modulation index of 5) to 80 kHz (with a modulation index of 10). This bandwidth represents a fraction of the available capacity of the typical Ku-band transponder, even considering that two such channels would be required for two-way voice communication.

Although not specified in the CSS Task Force Report, the possible use of 56 kbps digital SCPC should be considered. This capability is currently available on some systems and could be a viable alternative to analog SCPC communication.

NOTES - CHAPTER II

[1]CSS Task Force. Commercial Satellite Communications Survivability Report, May 20, 1983, p. 3-6.

[2]CSS Task Force. Addendum to Commercial Satellite Communications Survivability Report of May 20, 1983, December 15, 1983, p. 3-9.

[3]Walter L. Morgan. "Satellite Notebook: SBS-1." Satellite Communications, May 1981, p. 37.

[4]James Martin. Telecommunications and the Computer (Englewood Cliffs, NJ: Prentice-Hall, Inc., 1976), p. 304.

[5]Robert M. Gagliardi. Satellite Communications (Belmont, CA: Lifetime Learning Publications, 1984), p. 554, 104.

[6]S. W. Maley. Unpublished notes on modulation, p. 10.

[7]Gagliardi, p. 32.

CHAPTER III

EARTH STATION LOCATION

The physical location of the earth station is an important consideration for several reasons. Distance to the satellite, man-made or natural obstructions in the general area, weather patterns, and other sources of electromagnetic transmissions in the area are all important factors dealing with earth station location from a technical standpoint. While the strategic location of an earth station and its potential use to the government in a time of crisis or emergency are also important, this chapter will deal only with the technical considerations. For the purposes of this discussion, it will be assumed that the operational usefulness of an earth station will be determined by the government based on its own criteria and that the location considerations discussed here will be pertinent to any locations chosen by the government. It is important to keep in mind, however, that the CSS Task Force is approaching the subject of satellite survivability on the premise that only selected earth stations will be candidates for inclusion in the reconstitution plan. These locations will probably be determined largely by their proximity to specific government or defense facilities.

Satellite/Earth Station Geometry

The actual location of an earth station, expressed in terms of latitude and longitude, is used to determine the distance to a satellite in geosynchronous orbit. This distance is important because timing relationships, both in terms of time division multiplex access and data reception timing, are often detrmined by it. Since propagation delay is a direct function of distance, precise distance calculations are critical. The elevation angle and azimuth of the earth station antenna are two additional parameters determined by the position of the earth station relative to the satellite. These basic relationships are shown in Figure 3.1.

While a trigonometric proof is not necessary here, it can be shown that the distance from the earth station to the satellite (and, thus, the propagation delay), the earth station antenna elevation angle and the earth station antenna azimuth can be determined by knowing the longitude of the satellite as well as the longitude and latitude of the earth station.[1] In the following discussion, the following variables will be used:

A_s = latitude of the satellte

B_s = longitude of the satellite

A_e = latitude of the earth station

B_e = longitude of the earth station

(3.1) $d = B_s - B_e$

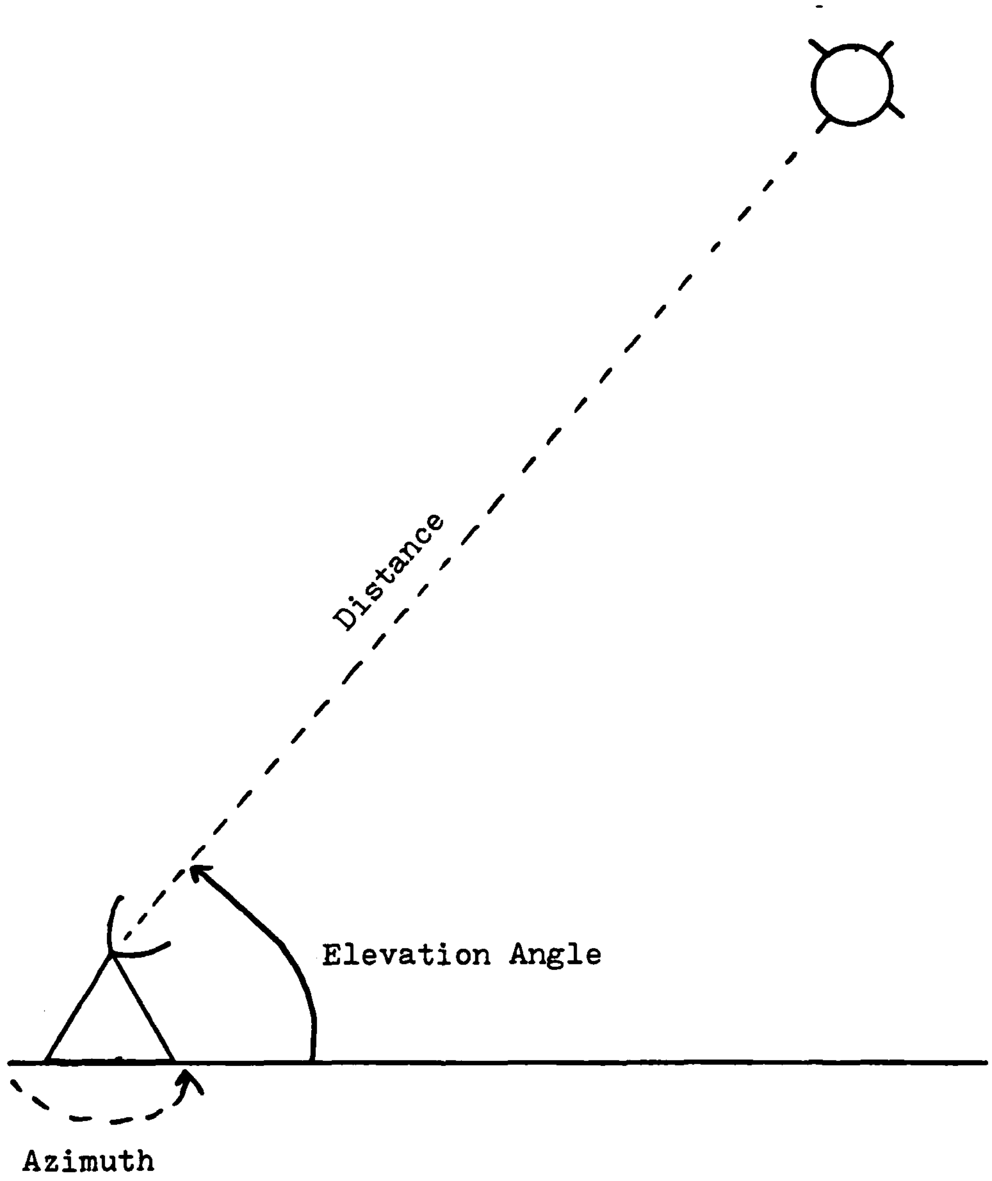


Figure 3.1. Satellite/Earth Station Antenna Relationships.

R = distance from the center of the earth to a geosynchronous satellite

= 3960 + 22282

= 26242 miles

R_e = radius of the earth

= 3960 miles

With these variable in mind, let:

$$V_a = R \cos A_s \cos d \sin A_e + R \sin A_s \cos A_e \quad (3.2)$$

$$V_b = R \cos A_s \sin d \quad (3.3)$$

$$V_c = R \cos A_s \cos d \cos A_e + R \sin A_s \sin A_e - R_e \quad (3.4)$$

The variables V_a, V_b, and V_c can then be used to calculate the earth station-to-satellite distance (in miles), the propagation delay (in seconds), the earth station antenna elevation angle (in degrees from the horizon), and the earth station antenna azimuth (in degrees) as follows:

$$\text{Distance} = \sqrt{V_a^2 + V_b^2 + V_c^2} \text{ miles} \quad (3.5)$$

$$\text{Delay} = \text{Distance}/186335 \text{ seconds} \quad (3.6)$$

$$\text{Elev Angle} = \text{Arctan}\ (V_c/\sqrt{V_a^2 + V_b^2}) \quad (3.7)$$

$$\text{Azimuth} = \text{Arctan}\ (V_b/V_a) \quad (3.8)$$

As an example, consider an earth station located within the continental United States (CONUS) communicating with a geosynchronous satellite (latitude = 0°) located at 100°W longitude. Table 3.1 presents the approximate coordinate boundaries of the CONUS, Alaska and Hawaii.

Table 3.1
Approximate Physical Boundaries of U.S. Areas[2]

Direction	CONUS	Alaska	Hawaii
East	67°W	140°W	155°W
West	125°W	170°E	161°W
North	49°N	71°N	22°N
South	25°N	52°N	19°N

For the purposes of this example, let the earth station be located in the northeastern United States at a latitude of 45°N and a longitude of 70°W. Substituting the values in the example in Equations 3.1 through 3.4, we get:

$$\begin{aligned} d &= 100 - 70 \\ &= 30 \end{aligned} \tag{3.1e}$$

$$\begin{aligned} V_a &= 26242 \cos 0 \cos 30 \sin 45 + \\ &\quad 26242 \sin 0 \cos 45 \\ &= 16069.877 \end{aligned} \tag{3.2e}$$

$$\begin{aligned} V_b &= 26242 \cos 0 \sin 30 \\ &= 13121 \end{aligned} \tag{3.3e}$$

$$V_c = 26242 \cos 0 \cos 30 \cos 45 +$$

(3.4e) $$26242 \sin 0 \sin 45 - 3960$$

$$= 12109.878$$

Applying these values to Equations 3.5 through 3.8 results in:

(3.5e) $$\text{Distance} = \sqrt{V_a^2 + V_b^2 + V_c^2}$$

$$= \sqrt{16069.877^2 + 13121^2 + 12109.878^2}$$

$$= 24021.88 \text{ miles}$$

(3.6e) $$\text{Delay} = \text{Distance}/186335$$

$$= 24021.88/186335$$

$$= 0.1209177 \text{ seconds}$$

(3.7e) $$\text{Elev Angle} = \text{Arctan } \frac{12109.878}{\sqrt{16069.877^2 + 13121^2}}$$

$$= 30.27^{\circ}$$

(3.8e) $$\text{Azimuth} = \text{Arctan } (13121/16069.877)$$

$$= 39.23^{\circ}$$

For a more detailed treatment of the trigonometry involved in satellite/earth station locations, see Fthenakis.[3]

Once the government has identified the earth stations it could use in a reconstitution plan (or, in a more comprehensive method, all possible earth stations), the preceding calculations could be performed against all U.S. Ku-band satellites in orbit above the United States. With the limited number of current and planned satellites, this task would require minimal effort and probably

should be part of a reconstitution data base along with other information to be developed in this model. Because satellites tend to drift a certain amount around their ideal orbital position, the calculations should be performed periodically with updated satellite positions to ensure accurate data in the event the reconstitution plan was put into effect.

Additional Site Considerations

In addition to geographic location, at least two other location factors must be considered to determine whether or not a given earth station can establish and maintain communication with a given satellite. These are physical obstructions in the transmission path and interference from other transmission sources.

Typically, earth stations are designed to work with a particular satellite orbiting at a particular position. Since satellite communications is line of sight, the position and location of the earth station must provide a clear, unobstructed path to the satellite. While this condition is sure to be met for the original communications link, it may be that there are physical obstructions (buildings, mountains, etc.) that would prohibit establishing a link in a new direction. Figure 3.2 presents a simple example using an elevation angle of 18.82°. Using the Law of Sines,

$$\frac{\text{Height}}{\sin E} = \frac{\text{Distance}}{\sin B} \qquad (3.9)$$

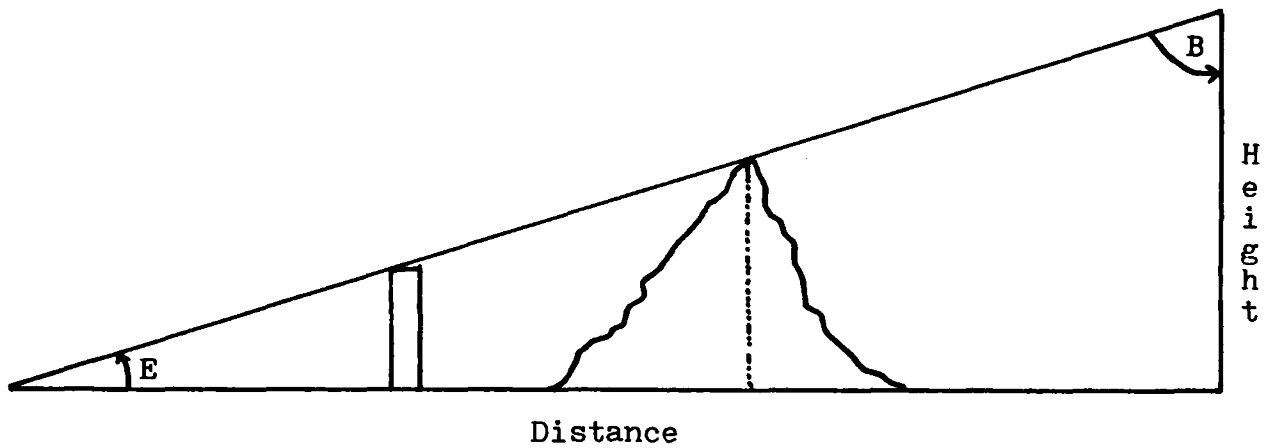


Figure 3.2. Line-of-Sight Obstruction Geometry.

If angle E is 18.82^{0}, then angle B is 71.18^{0}. Table 3.2 shows some sample heights that would be incident to the line of sight at the given distances. Although the curvature of the earth would actually allow these heights to be somewhat greater, the curvature effect would be negligible for the practical heights and distances involved. This would be least likely to occur when attempting to establish communications with a new satellite close to the orbital position of the original satellite because the actual antenna movement would be relatively slight. In any case, this possibility must be considered when attempting to use an earth station to establish a communications link with a new satellite.

Table 3.2
Sample Obstruction Heights and Distances

Height (ft.)	Distance (mi.)
899	0.5
1,800	1.0
2,699	1.5
3,599	2.0
4,499	2.5
5,399	3.0
6,298	3.5
7,198	4.0
8,098	4.5
8,998	5.0
9,987	5.5
10,797	6.0
11,697	6.5
12,597	7.0
13,496	7.5
14,396	8.0
15,296	8.5
16,196	9.0
17,095	9.5
17,995	10.0

The CSS Task Force points out that many potential reconstitution earth stations may be private corporate terminals located on the top of tall buildings.[4] Under catastrophic conditions, access to rooftop terminals may be impaired (such as inoperable elevators or impassable stairwells) or there may be a problem getting power to the terminal if rooftop emergency power is not available. The presence of these conditions may make a particular rooftop earth station unattractive for possible reconstitution use or, in extreme cases, may preclude a station from being considered at all.

Electromagnetic interference is another factor that reconstitution planners must recognize. While system designers must include a survey of sources of interference in their original earth station design, pointing the antenna in a new direction will require a re-evaluation of this issue to determine whether or not there are potential sources of interference. While C-band earth stations are more susceptible to this problem due to their sharing of the 4/6 GHz portion of the spectrum with terrestrial microwave, it must still be considered when re-positioning the antenna of a Ku-band station.

NOTES - CHAPTER III

[1]Hussain Haddad. Lecture notes from "Trends in Satellite Communications Systems," University of Colorado, Spring Semester 1985.

[2]Hammond World Atlas (Maplewood, NJ: Hammond, Inc., 1981), pp. 197, 204, 212, 219, 242.

[3]Emanuel Fthenakis. Manual of Satellite Communications (New York, NY: McGraw-Hill Book Co., 1984), p. 114.

[4]CSS Task Force. Addendum to Commercial Satellite Communications Survivability Report of May 20, 1983, December 15, 1983, p. 3-4.

CHAPTER IV

LINK ANALYSIS

The quality of a satellite link can be determined by performing a link analysis on a given satellite channel. A rather detailed list of parameters used in the analysis is shown in Table 4.1 for a typical 12/14 GHz link.[1]

Although Table 4.1 lists nine different sources of gains and losses, they can be conceptually grouped as transmitter parameters, path parameters, and receiver parameters. From Table 4.1, items 1, 2, and 3 are transmitter parameters and can be grouped and referred to as effective isotropically radiated power (EIRP). Items 4 and 5 are path parameters and items 6, 7, and 8c are the receiver parameters often referred to as the figure of merit (G/T).[2] Thus, the carrier-to-noise ratio (CNR) can be represented as:

$$CNR = (EIRP)\ (\text{Propagation loss})\ (G/T)\ (1/kB)$$

where:

EIRP	=	(transmit power) (transmit antenna gain)
Propagation loss	=	(atmospheric loss) x (free space loss) x (weather loss)
G/T	=	receive antenna gain/receiver noise temperature
k	=	Boltzman's Constant (1.379×10^{-23})
B	=	RF bandwidth (in hertz).

Table 4.1
Typical 12/14 GHz Link Parameters

Up-Link

1.	Transmitter power, dBW	25	
2.	Transmitter system loss, dB	- 1	
3.	Transmitting antenna gain, dB	46	
4.	Atmospheric loss, dB	- 0.5	
5.	Free space loss, dB	-208	
6.	Receiving antenna gain, dB	46	
7.	Receiver system loss, dB	- 1	
	Received power, dBW	- 93.5	
8a.	Noise temperature, ^{o}K		1000
8b.	Received bandwidth, MHz		36
8c.	Noise, dBW	123	
	Received CNR, dB	29.5	
9.	Loss in bad storm, dB	- 10	
	Received CNR in bad storm, dB	19.5	

Down-Link

1.	Transmitter power, dB	20	
2.	Transmitter system loss, dB	- 1	
3.	Transmitting antenna gain, dB	44	
4.	Free space loss, dB	-206	
5.	Atmospheric loss, dB	- 0.6	
6.	Receiver antenna gain, dB	44	
7.	Receiver system loss, dB	- 1	
	Received power, dBW	-100.6	
8a.	Noise temperature, ^{o}K		1000
8b.	Received bandwidth, MHz		36
8c.	Noise, dBW	123	
	Received CNR, dB	22.4	
9.	Loss in bad storm, dB	- 10	
	Received CNR in band storm, dB	12.4	

NOTES: Satellite antenna: 1.8 meters
Earth station antenna: 1.8 meters
Low-cost earth station receiver

Specific data relating to the link analysis for current (and near term) U.S. domestic Ku-band satellite systems are presented in Table 4.2.

Table 4.2
U.S. Domestic Ku-Band Satellite Parameters

System	Number of Transponders/ Bandwidth (MHz)	EIRP (dBW)	G/T (dB/K)
SBS[3]	10/43	37.1-44.1	-4.5 to 2.1
Satcom	16/54	44-50[4]	1 to 6[5]
Spacenet[6]	6/72	35.8-44.3	-1.4 to 1.5
GSTAR[7]	16/54	38-45	-3.7 to 3.3
Amsat[8]	6/72	35.8-44.3	-1.4 to 1.5

Path Loss

To determine the free space path loss, the distance from transmitter to receiver must be known. In the case of a link with a geosynchronous satellite, the distance can be computed as follows:

$$D = R_e\sqrt{44.7794 - 13.2332\ (\cos LAT \cos LONG_1 - LONG_2)}$$

where:

D = distance from earth station to satellite

R_e = radius of the earth

= 3,960 miles

= 6,371,640 meters

LAT = latitude of the earth station in degrees

$LONG_1$ = longitude of the earth station in degrees

$LONG_2$ = longitude of the satellite in degrees.

The computed distance can then be used in the formula:

$$L_p = 10 \log \left[\frac{w}{4(pi)D}\right]^2$$

where:

L_p = free space path attenuation

w = wavelength of the signal in meters

= 2.9979×10^8/frequency in hertz

pi = 3.1416

D = distance in meters.

Weather-Related Loss

Weather-related loss is caused by rain, fog, clouds, snow, and hail in the atmosphere. Ippolito, Kaul, and Wallace have accumulated extensive data related to atmospheric loss and presented them in a NASA reference publication titled Propagation Effects Handbook for Satellite Systems Design. Subtitled "A Summary of Propagation Impairments on 10 to 100 GHz Satellite Links With Techniques for System Design," the handbook is in its third edition and the material presented in this section is drawn from that publication.

Rain Attenuation

Ippolito, et al., present seven different models for approximating attenuation due to rainfall as well as theoretical data

relating to the development of the models. Because of its relative simplicity and straightforward approach, the Global Model developed by Crane and Blood is presented here and suggested for use in the overall interoperability model.[9]

The path attenuation caused by rain can be approximated by the relationship

$$A = L\ r\ a\ R_p{}^b$$

where:

A	=	path attenuation
L	=	length of the propagation path
r	=	effective path average factor
R_p	=	point rainfall rate exceeded P percent of the time
a,b	=	coefficients used to estimate specific attenuation for a given rain rate.

While the model is fully developed in the handbook, a simple step-by-step method of computing the rain attenuation estimation will be presented here for inclusion in the link analysis.

Depending on whether or not specific rainfall data are available for the specific earth station site being considered, one of two approaches should be used. If the actual data are available, use steps 1a and 2a. Otherwise, steps 1b and 2b (which use approximated rainfall rates by geographic region) should be used. Both methods use steps 3 through 7 and require the earth station location and elevation, elevation angle, and frequency as givens.

Step 1a. Obtain rainfall statistics from Weather Service data or actual site measurements. A sample chart is shown in Figure 4.1.

Step 1b. For the earth stations latitude and longitude, obtain the appropriate climate region using Figure 4.2 for locations within the Continental United States and Canada or Figure 4.3 (or an appropriate regional chart) for other locations.

Step 2a. Select probabilities of exceedance, P, covering the range of interest (e.g., .01, .1, or 1 percent). Based on the selected value of P, obtain the measured point rain rate, R_p mm/hr.

Step 2b. Select probabilities of exceedance, P, covering the range of interest (e.g., .01, 1, or 1 percent). Using Table 4.3, select the terminal point rain rate, R_p mm/hr, corresponding to the selected values of P.

Step 3. For a link through the entire atmosphere, obtain the rain layer height from the height of the 0^o isotherm (melting layer), H_o, based on the earth station latitude using the chart in Figure 4.4. The heights will vary with the probabilities of exceedance, P.

Step 4. Calculate the horizontal path projection, D, of the oblique path through the rain volume.

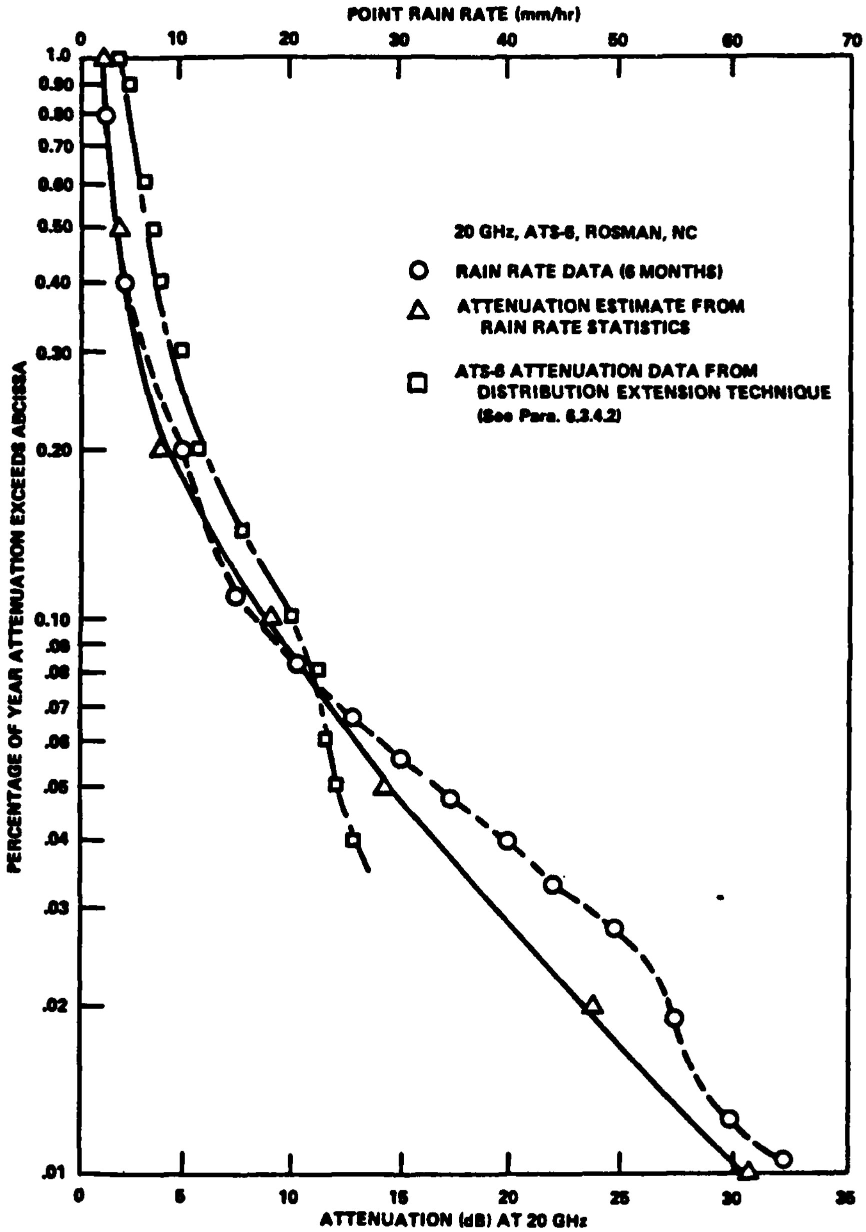


Figure 4.1. Sample Rain Attenuation Chart.

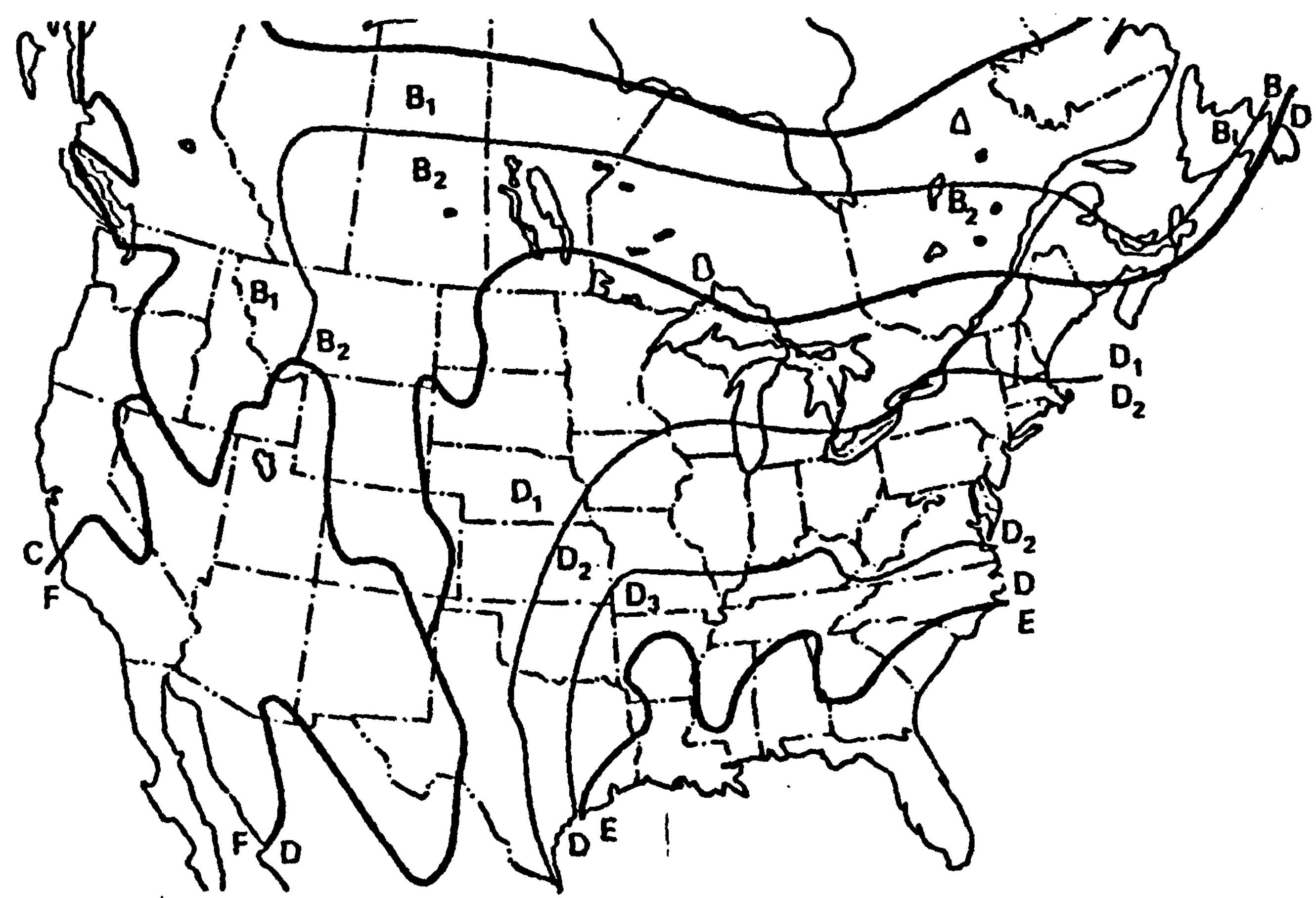


Figure 4.2. Rain Rate Climate Regions for the Continental United States and Southern Canada.

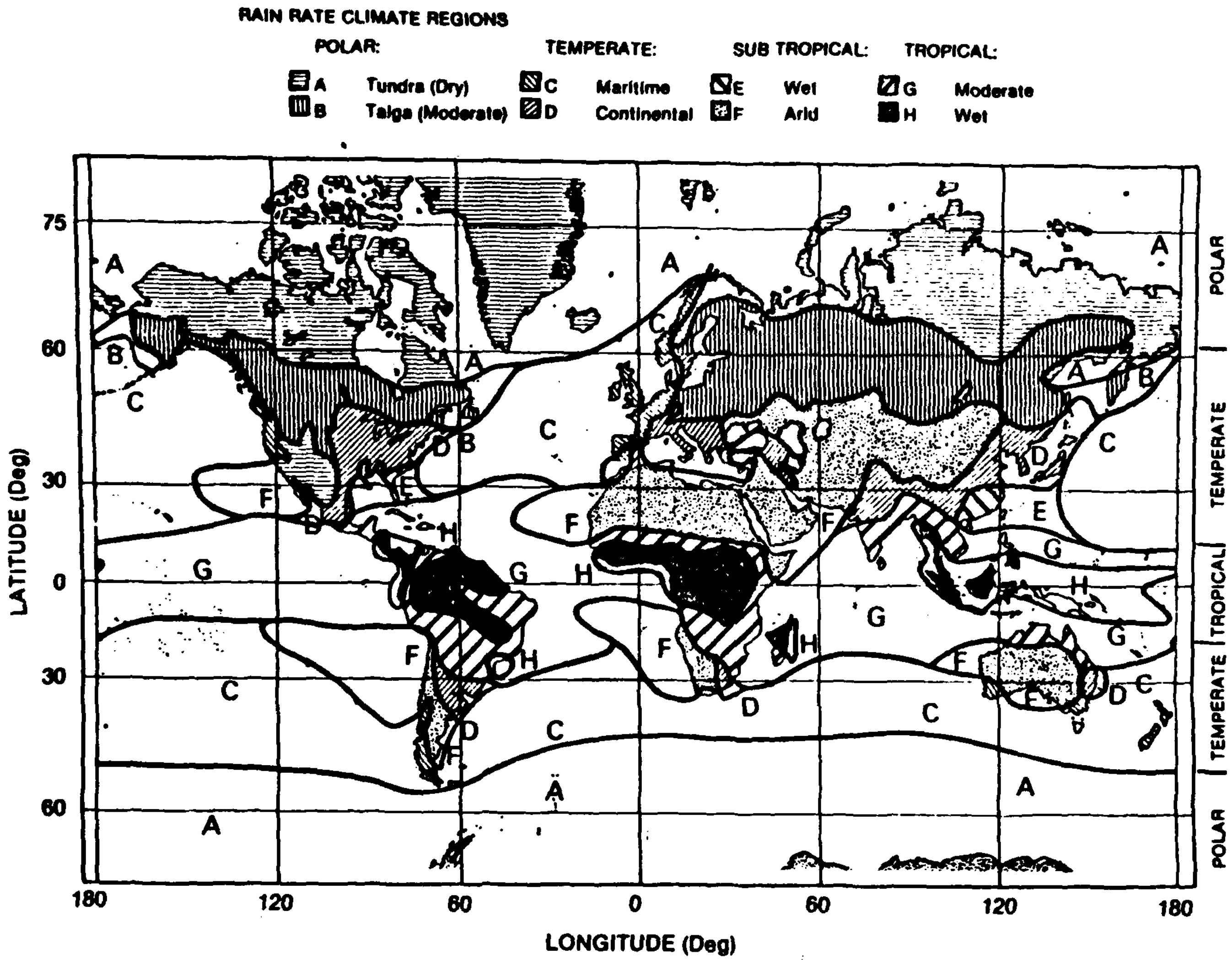


Figure 4.3. Global Rain Rate Climate Regions.

Table 4.3
Point Rain Rate Distribution Values (mm/hr)
Versus Percent of Year Rain Rate is Exceeded

Percent of Year	RAIN CLIMATE REGION												Minutes per Year	Hours per Year
	A	B_1	B	B_2	C	D_1	$D=D_2$	D_3	E	F	G	H		
0.001	28.5	45	57.5	70	78	90	108	126	165	66	185	253	5.26	0.09
0.002	21	34	44	54	62	72	89	106	144	51	157	220.5	10.5	0.18
0.005	13.5	22	28.5	35	41	50	64.5	80.5	118	34	120.5	178	26.3	0.44
0.01	10.0	15.5	19.5	23.5	28	35.5	49	63	98	23	94	147	52.6	0.88
0.02	7.0	11.0	13.5	16	18	24	35	48	78	15	72	119	105	1.75
0.05	4.0	6.4	8.0	9.5	11	14.5	22	32	52	8.3	47	86.5	263	4.38
0.1	2.5	4.2	5.2	6.1	7.2	9.8	14.5	22	35	5.2	32	64	526	8.77
0.2	1.5	2.8	3.4	4.0	4.8	6.4	9.5	14.5	21	3.1	21.8	43.5	1052	17.5
0.5	0.7	1.5	1.9	2.3	2.7	3.6	5.2	7.8	10.6	1.4	12.2	22.5	2630	43.8
1.0	0.4	1.0	1.3	1.5	1.8	2.2	3.0	4.7	6.0	0.7	8.0	12.0	5260	87.7
2.0	0.1	0.5	0.7	0.8	1.1	1.2	1.5	1.9	2.9	0.2	5.0	5.2	10520	175
5.0	0.0	0.2	0.3	0.3	0.5	0.0	0.0	0.0	0.5	0.0	1.8	1.2	26298	438

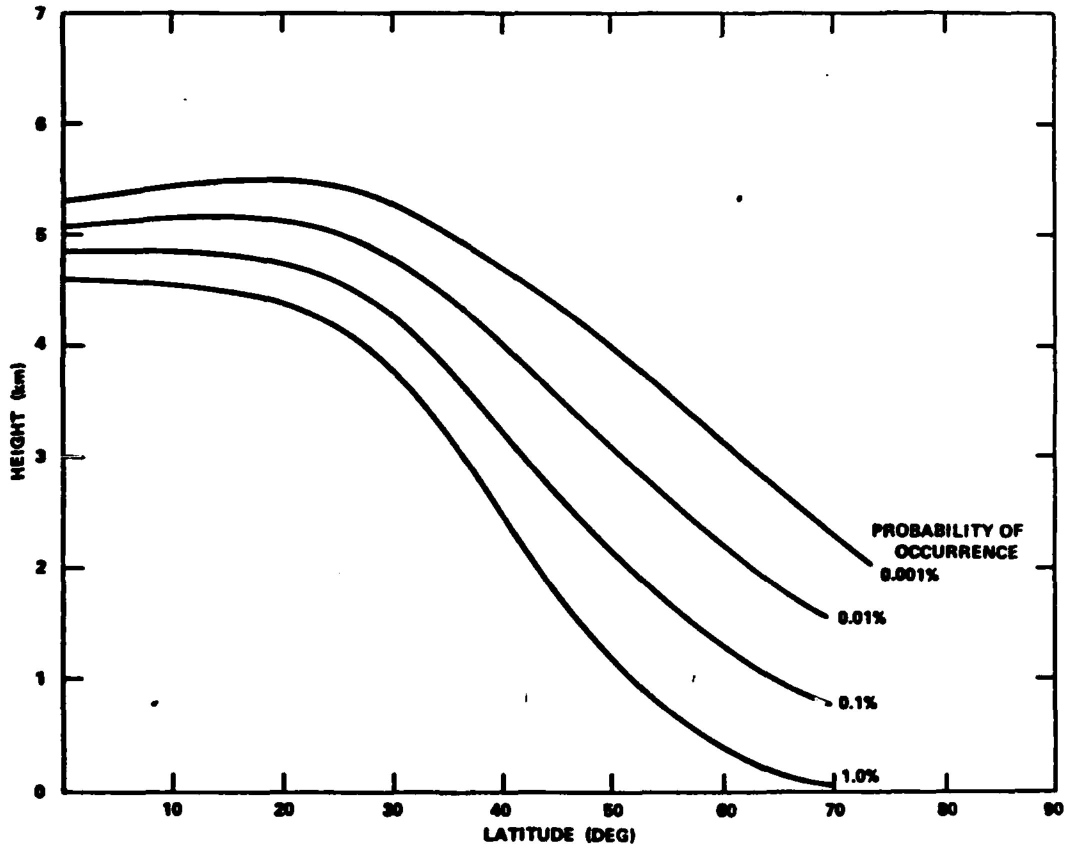


Figure 4.4. Latitude Dependence of the Rain Layer 0^{o} Isotherm Height as a Function of Probability of Occurrence.

For an elevation angle, E, greater than or equal to 10^o,

$$D = \frac{H_o - H_g}{\tan E}$$

where:

H_o = height (km) of isotherm for probability P

H_g = height (elevation) of the ground terminal (km)

E = elevation angle.

If D is equal to or less than 22.5 km, then proceed to step 5. Otherwise, the path is assumed to have the same attenuation value as for a 22.5 km path but the probability of exceedance is adjusted by the ratio of 22.5 km to the path length:

$$P' = P\ (22.5/D)$$

Step 5. Using Table 4.4, obtain the attenuation parameters, a and b. For rain rates of 30 mm/hr or less, select from the "Low" columns. Select from the "High" columns for rain rates in excess of 30 mm/hr.

Table 4.4
Values for a and b in aR^b as a Function of Frequency

Freq.	a		b	
(GHz)	Low	High	Low	High
10	1.17×10^{-2}	1.14×10^{-2}	1.178	1.189
11	1.50×10^{-2}	1.52×10^{-2}	1.171	1.167
12	1.86×10^{-2}	1.96×10^{-2}	1.162	1.150
15	3.21×10^{-2}	3.47×10^{-2}	1.142	1.119

Step 6. Using the R_p value corresponding to the exceedance probability of interest, calculate the empirical constants X, Y, Z, and U using:

$$X = 2.3\ R_p^{-0.17}$$

$$Y = 0.026 - 0.03\ \ln R_p$$

$$Z = 3.8 - 0.6\ \ln R_p$$

$$U = \frac{\ln(Xe^{YZ})}{Z} \quad .$$

Step 7. If Z is equal to or less than D, compute the total attenuation due to rain exceeded for P percent of the time when the elevation angle is equal to or less than 10° using:

$$A = \left[\frac{aR_p^{\ b}}{\cos E}\right]\left[\frac{E^{UZb}-1}{UB} - \frac{X^b e^{YZb}}{Yb} + \frac{X^b e^{YDb}}{YB}\right]$$

where:

A = total path attenuation due to rain (dB)

a,b = parameters relating the specific attenuation to rain rate (from step 5)

R_p = point rain rate

E = elevation angle

D = horizontal path projection length (from step 4).

If D is less than Z, then

$$A = \frac{aR_p{}^b}{\cos E}\left[\frac{e^{UZb}-1}{Ub}\right]$$

The preceding procedure results in an estimate for the attenuation, A, exceeded for P percent of the year. (An example of this procedure is included in a sample link analysis in the latter part of this chapter.) While the procedure would be somewhat cumbersome manually for a large number of calculations, it would lend itself easily to automation as part of a reconstitution or interoperability data base. Because rain fade can be sizeable, it should be included in link analyses. Where the "good weather" link is marginal, rain fade may take the signal off the air. Under normal circumstances, a system planner would modify system hardware to ensure the rain fade was compensated for. In the case of reconstitution, planners will be able to use rain attenuation data along with the other link analysis factors to determine the reliability of a signal (and, thus, the information it carries) at critical earth stations.

Other Atmospheric Attenuation

Clouds, fog, and blowing sand or dust are additional sources of atmospheric attenuation. Although there are theoretical losses due to these sources, Ippolito, et al., contend they are almost negligible for Ku-band signals. If deemed appropriate, a total of 3 dB loss could be used for clouds and fog and an additional 1 dB loss might be encountered in a sand or dust storm.[10]

A Sample Analysis

As an example of link analysis, let us take an SBS satellite at 99°W (see Table 4.5) transmitting at 12 GHz linking earth stations in Maine (70°W, 44°N, elevation of 500 feet) transmitting at 15 GHz and California (123°W, 38°N, elevation of 100 feet). Using the worst case SBS numbers from Table 4.2, we get an EIRP of 37.1 dB and G/T of -4.5 dB/°K. For this example, the uplink transmitter and downlink receiver parameters from Table 4.1 will be used.

Table 4.5
U.S. Domestic Ku-Band Satellite Assigned Locations[11]

System	Satellite	Position
SBS	SBS-1	99°W
	SBS-2	97°W
	SBS-3	95°W
	SBS-4	101°W
	SBS-5	124°W
Satcom	K-1	87°W
	K-2	126°W
Spacenet	Spacenet 1	120°W
	Spacenet 2	69°W
	Spacenet 3	91°W
GSTAR	A1	105°W
	A2	103°W
Amsat	ASC-1	128°W
	ASC-2	81°W

Using the uplink transmitter figures from Table 4.1 for the Maine earth station and the downlink receiver values from the table for the California station, we get the following:

$$EIRP_{Maine} = P_t + L_t + G_t$$
$$= 25 + (-1) + 46$$
$$= 70 \text{ dB}$$

where:

P_t = transmitter power in dB

L_t = transmitter system loss in dB

G_t = gain of transmitting antenna in dB.

Applying the distance formula to the earth stations, we get:

$$D_{Maine} = 3960 \sqrt{44.7794-13.2332\left[\cos(44)\cos(99-70)\right]}$$
$$= 23{,}909.268 \text{ miles}$$
$$(23909.268) \quad (1609)$$
$$= 3.8470012 \times 10^7 \text{ meters}$$

$$D_{Calif} = 3960 \sqrt{44.7794-13.2332\left[\cos(38)\cos(99-123)\right]}$$
$$= 23{,}512.21 \text{ miles}$$
$$(23512.21) \quad (1609)$$
$$= 3.7831145 \times 10^7 \text{ meters.}$$

The propagation loss from Maine to the satellite is then:

$$L_{P(Maine)} = \left[\frac{0.01999}{4(pi)\ (3.8470012 \times 10^7)}\right]^2 = -207.7 \text{ dB}$$

and the path loss from the satellite to California is:

$$L_{P(Calif)} = \left[\frac{0.02498}{4(pi)\ (3.7831145 \times 10^7)}\right]^2 = -205.6\ \text{dB}$$

To calculate the weather loss for the Maine link, we will apply the seven-step procedure presented in the "Weather-Related Loss" section of this chapter.

Step 1b. From Figure 4.2, identify climate area for this location in Maine. In this case, the area is D1.

Step 2b. In this example, let us assume that we can afford to lose our signal for up to one hour per year. At the .01 percent level, we would expect the rainfall to exceed the level of 35.5 mm/hr 52.6 minutes per year. This is the rainfall rate we will select.

Step 3. Based on the 44^{o}N latitude of the Maine earth station and the .01 percent probability selected in Step 2b, we determine from Figure 4.4 that the height of the rain layer is 3.8 kilometers.

Step 4. Having determined that the elevation angle, E, is 31.6^{o}, we determine the distance through the rain layer by:

$$D = \frac{H_o - H_g}{\tan E}$$

$$= \frac{3.8 - 0.1515}{\tan 31.6}$$

$$= 5.93\ \text{km.}$$

Step 5. Since the rain rate determined in Step 2b is 35.5 mm/hr, we select the high values for a and b from Table 4.4. For the 15 GHz uplink frequency, a is 3.47×10^{-2} and b is 1.119.

Step 6. Using the R_p value of 35.5 mm/hr, we calculate the empirical constants X, Y, Z, and U.

$$X = 2.3(35.5^{-0.17})$$

$$= 1.2536867$$

$$Y = 0.026 - 0.03\ (\ln 35.5)$$

$$= -0.081086$$

$$Z = 3.8 - 0.6\ (\ln 35.5)$$

$$= 1.6582804$$

$$U = \frac{\ln(1.2536867\ e^{(-0.081086)(1.6582804)})}{1.6582804}$$

$$= 0.0552523$$

Step 7. Because Z is less than D, we calculate the rain attenuation as follows:

$$A' = \left[\frac{aR_p{}^b}{\cos E}\right]\left[\frac{e^{UZb}-1}{Ub} - \frac{X^b e^{YZb}}{Yb} + \frac{X^b e^{YDb}}{Yb}\right]$$

$$= 12.5 \text{ dB}$$

Adding a fog and cloud margin of 3 dB, we get a total weather-related loss of 15.5 dB.

Thus, the total propagation loss is:

$$L_P = L_{P(Maine)} + L_a + L_w$$

$$= -207.7 + (-0.5) + (-15.5)$$

$$= -223.7 \text{ dB}$$

where:

L_P = total propagation loss in dB

L_P(Maine) = free space path loss in dB

L_a = atmospheric loss in dB

L_w = weather loss in dB.

The G/T of the satellite is -4.5 dB/^{o}K and 1/kB is

$$= \frac{1}{(1.38 \times 10^{-23})(4.3 \times 10^{7})} = 152.3 \text{ dB}$$

Thus, the CNR for the uplink is:

$$CNR_u = 70 + (-223.7) + (-4.5) + 152.3$$
$$= -5.9 \text{ dB.}$$

Applying the same technique to the downlink, we get a CNR of:

$$CNR_d = 37.1 + (-211.7) + 13 + 152.3$$

$$= -9.4 \text{ dB.}$$

From Gagliardi,[12] a link CNR can be calculated as follows:

$$(CNR)^{-1} = (CNR_u)^{-1} + (CNR_d)^{-1}$$

or

$$(CNR)^{-1} = (0.2570396)^{-1} + (0.1148154)^{-1}$$

$$= \frac{1}{0.2570396} + \frac{1}{0.1148154}$$

$$= 3.8904511 + 8.7096359$$

$$= 12.6$$

$$CNR = \frac{1}{12.6}$$

$$= 0.0793645$$

$$= -11 \text{ dB}.$$

In this case, the minimum CNR would not be achieved. Using the best case figures for the SBS satellite (EIRP of 44.1 and G/T of 2.1), the CNR is -4.1 dB. In Chapter II, we established a minimum required CNR of 10 dB. In this sample analysis, even the best case situation would not meet the required minimum signal level. Neither level would even meet the theoretical minimum level of .11 dB. If nothing else, this example should emphasize the importance of performing link analyses in conjunction with the other factors of interoperability planning. Obviously, in an actual evaluation, the appropriate EIRP and G/T data from the actual earth stations would be used. These data are available from earth station applications filed with the FCC.

NOTES - CHAPTER IV

[1]James Martin. Communications Satellite Systems (Englewood Cliffs, NJ: Prentice-Hall, Inc., 1978), p. 131.

[2]Robert M. Gagliardi. Satellite Communications (Belmont, CA: Lifetime Learning Publications, 1984), p. 104.

[3]Walter L. Morgan. "Satellite Notebook: SBS-1," Satellite Communications, May 1981, p. 37.

[4]Walter L. Morgan. "RCA Satcom 14/12 GHz Satellites," Satellite Communications, February 1984, p. 46.

[5]RCA. "Ku-Band Satellite System," RCA American Communications, undated.

[6]GTE Spacenet. "Spacenet Satellites Technical Specifications," GTE Spacenet Corp., December 12, 1984, p. 14.

[7]GTE Satellite. "GSTAR Satellites Technical Specifications," GTE Satellite Corp., December 12, 1984, p. 14.

[8]Robert Trobau (Staff engineer, American Satellite Corp.). Telephone conversation, April 15, 1985.

[9]Louis J. Ippolito, et al. Propagation Effects Handbook for Satellite Systems Design. NASA Reference Publication 1083(03), June 1983, p. 228.

[10]Ibid., p. 270.

[11]Federal Communications Commission. "U.S. Domestic Satellites," undated.

[12]Gagliardi, p. 116.

CHAPTER V

ANTENNA AND FREQUENCY AGILITY

In Chapter III, the subject of earth station location was addressed. In particular, it was pointed out that there are factors to consider when positioning the antenna in a new direction, such as the possibility of obstacles in the line of sight or sources of electromagnetic interference that were not involved in the original signal path. Assuming that antenna re-orientation is required to use a given earth station in a new link, the degree to which an antenna can be physically moved and the degree of effort required to do so is a significant issue and must be considered in advance. In addition, the ability to properly align the antenna for the proper polarization and the ability of the terminal receiver and transmitter to be tuned to new frequencies must be considered.

Antenna Agility

With the advent of geosynchronous satellites, complicated earth station antenna pointing systems were, by and large, eliminated. Because of the relatively stable position of the satellites, antennas can be pointed in a given direction and left there with little or no subsequent adjustment. Walthall[1] characterizes current antenna mounts and positioning capability according to the perfor-

mance level of the earth station. High-performance stations, such as common carrier gateway stations, are likely to have the most physically agile antenna systems because of their critical control functions. For medium-performance terminals, the antennas are usually fixed with some capability to be manually adjusted in elevation and azimuth. Minimum performance earth stations are likely to have little steering ability. It might be possible to loosen the mounts on these antennas to gain some degree of re-positioning. It should be noted that the vast majority of earth stations in use today are of the medium- and low-performance variety and, thus, will have limited re-positioning capability. It would seem prudent to include the re-positioning limits of an antenna, in terms of elevation and azimuth, when accumulating data on an earth station for use in a reconstitution data base. To the extent that an antenna cannot be accurately positioned, pointing error will occur.

Pointing error occurs when an antenna is not correctly positioned in relation to the antenna on the other end of the link. This may occur due to an inability to aim the antenna in exactly the correct direction or inaccurate knowledge of the target location. According to Gagliardi,[2] pointing errors are usually in the range of 0.1 to 0.5 degrees. The presence of a pointing error means that the power to the receiver is determined by the antenna gain on the outer portion of the pattern rather than by the peak gain. The antenna gain at a given pointing error, p, can be expressed as:

$$g(p) = g\, e^{-2.76(p/b)}$$

where:

g = peak gain

p = pointing error

b = half power beamwidth

g(p) = gain at a given pointing error, p.

When narrow beamwidths are used, the pointing error becomes even more critical. Since the beamwidth depends directly on the diameter/wavelength ratio, the pointing error losses increase exponentially with this product. Figure 5.1 shows the resulting gain with the presence of differing amounts of pointing error for a range of diameter/wavelength ratios.

The problem of pointing error is likely to become more critical as the result of closer orbital spacing. In the Summer of 1983, the Federal Communications Commission ruled that fixed-service communications satellites in geosynchronous orbit should be placed every two degrees along the equatorial arc instead of their former four-degree spacing. The ruling stated that all new earth station antennas built after July 1, 1984, would have to accommodate the closer spacing and that antennas installed prior to that date would have to be modified by January 1, 1987 to meet the new standards.[3] Although there are other measures that can be used to alleviate the increased interference resulting from closer spacing, narrower beamwidths are almost certainly required.[4]

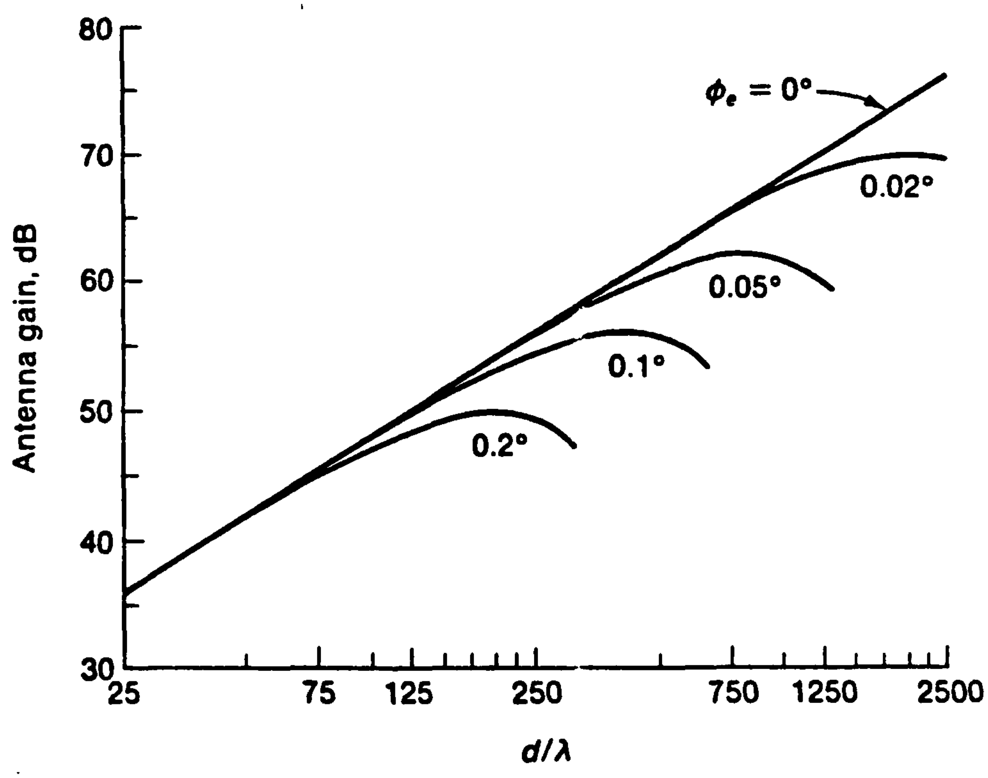


Figure 5.1. Pointing Error Loss in Antennas.
(ϕ_e = pointing error, antenna efficiency = 55%)

As the beamwidth decreases, greater care will have to be taken for accurate antenna positioning to avoid unacceptable levels of pointing error. To the extent that pointing error occurs or is anticipated, the decrease in gain should be included as an adjustment in the EIRP or G/T values used in a link analysis.

Antenna Polarization

In order to increase channel capacity on a given frequency, many current satellites employ orthogonal polarization to effectively create two channels on one frequency. Orthogonal polarization is simply the transmission of two signals whose electromagnetic fields are oriented 90 degrees from each other. Although the actual angles may be skewed somewhat, the two planar directions are typically referred to as "horizontal" and "vertical." Although circular polarization is feasible, it appears that linear polarization offers better performance.[5]

The ability of an earth station antenna to be placed in proper polarization with the antenna at the opposite end of the link must, therefore, be considered, as well as the ability to achieve the necessary elevation angle and azimuth. To the extent that proper polarization cannot or is not achieved, a certain level of cross-coupling interference from the orthogonally polarized signal at the same frequency can be expected.

Even when the proper orientation can be achieved, depolarization can be caused by rainfall. Figure 5.2 shows some reported

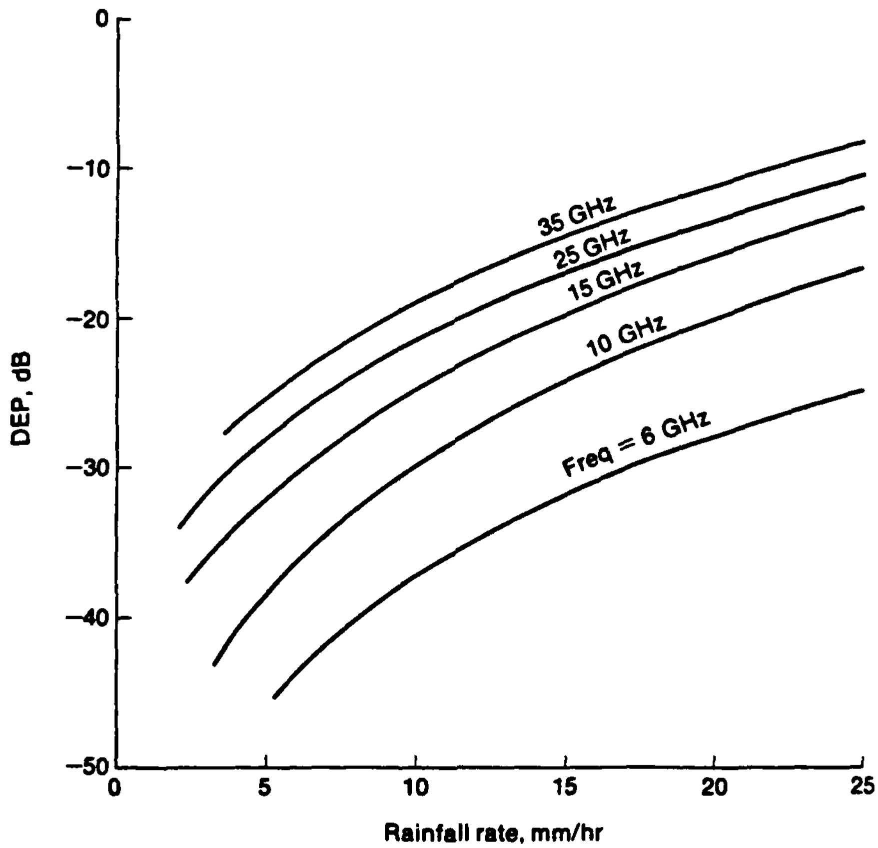


Figure 5.2. Depolarization vs. Rainfall Rate and Frequency. (Worst case polarization, 5 km path)

"worst case" depolarization losses reported by Gagliardi.[6] In addition to providing an additional consideration for link analyses, the graph emphasizes the importance of avoiding or compensating for depolarization. Additional sources of depolarization interference are impedance mismatch at the antenna ports, differential phase shift introduced by the polarizer, differential amplitude effects on the wave components, waveguide anomalies such as dispersion of beam and differential phase shift, reflector asymmetries and subreflector misalignment, Faraday rotation, and multipath effects.[7]

Frequency Agility

Of the five types of Ku-band satellites in orbit or soon to be launched, there are at least four different frequency plans. The four different plans are presented in Table 5.1. If an earth station is to communicate with a satellite other than one it was designed for, then the terminal must be able to tune its transmitter and receiver to the frequencies used by the new satellite.

Table 5.1
Frequency/Polarization Plans

Transponder	GSTAR		Satcom K	
	Up	Down	Up	Down
1	14.030V	11.738H	14.0290V	11.7290H
2	14.091V	11.791H	14.0585H	11.7585V
3	14.152V	11.852H	14.0880V	11.7880H
4	14.213V	11.913H	14.1175H	11.8175V
5	14.274V	11.974H	14.1470V	11.8470H
6	14.335V	12.036H	14.1765H	11.8765V
7	14.396V	12.096H	14.2060V	11.9060H
8	14.475V	12.157H	14.2355H	11.9355V

Table 5.1 (Continued)

Trans-ponder	GSTAR Up	GSTAR Down	Satcom K Up	Satcom K Down
9	14.044H	11.744V	14.2650V	11.9650H
10	14.105H	11.805V	14.2945H	11.9445V
11	14.166H	11.866V	14.3240V	12.0240H
12	14.227H	11.927V	14.3535H	12.0535V
13	14.288H	11.988V	14.3830V	12.0830H
14	14.349H	12.049V	14.4125H	12.1125V
15	14.410H	12.110V	14.4420V	12.1420H
16	14.471H	12.171V	14.4715H	12.1715V

Frequencies in GHz   V = Vertical   H = Horizontal

Trans-ponder	ASC & Spacenet Up	ASC & Spacenet Down	SBS Up	SBS Down
1	*	*	14.025V	11.725H
2	*	*	14.074V	11.774H
3	*	*	14.123V	11.823H
4	*	*	14.172V	11.872H
5	*	*	14.221V	11.921H
6	*	*	14.270V	11.970H
7	*	*	14.319V	12.019H
8	*	*	14.368V	12.068H
9	*	*	14.417V	12.117H
10	*	*	14.466V	12.166H
11	*	*	-	-
12	*	*	-	-
13	*	*	-	-
14	*	*	-	-
15	*	*	-	-
16	*	*	-	-
17	*	*	-	-
18	*	*	-	-
19	14.040V	11.740H	-	-
20	14.120V	11.820H	-	-
21	14.200V	11.900H	-	-
22	14.280V	11.980H	-	-
23	14.360V	12.060H	-	-
24	14.440V	12.140H	-	-

Frequencies in GHz   V = Vertical   H = Horizontal   * = C-band

Without considering the polarizations used, the center frequencies differ from one frequency to the next by anywhere from 0.5 to 29.5 MHz with an average difference of 9.4 MHz. As a rule of thumb, major high-performance earth stations such as gateway terminals should be able to tune across a range of 500 MHz and single channel user terminals could be expected to tune 40 MHz on either side of their routine frequency.[8] Thus, even medium- to low-performance earth stations should be able to tune to several frequencies on either side of their primary frequency. The actual tuning range of a given earth station would be a pertinent piece of data to include in an interoperability data base. Given the center frequencies of the established satellite channels and the frequency agility of an earth station, planners could determine ahead of time the possible alternate satellite transponders a given earth station could use.

While antenna agility, polarization, and frequency agility are limiting factors when considering interoperability, there appears to be sufficient flexibility available to allow a given earth station to be used on one or more alternate links. The nature of the variables is such that planners could predetermine those earth station/satellite links that are possible for a given earth station.

NOTES - CHAPTER V

[1]Harry L. Van Trees, ed. Satellite Communications (New York, NY: IEEE Press, 1979), p. 581.

[2]Robert M. Gagliardi. Satellite Communications (Belmont, CA: Lifetime Learning Publications, 1984), p. 93.

[3]Trudy E. Bell. "Technology '84: Communications," IEEE Spectrum, January 1984, p. 55.

[4]Walter H. Braun. "2^{o} Spacing: Its Impact on Domestic Satellite Systems," Satellite Communications, November 1981, p. 32.

[5]P. A. Watson and C. J. Soutter. "Dual Polarization Frequency Re-use in Satellite Communications Systems at 11 GHz," International Conference on Satellite Communication Systems Technology. (London: Whitefriars Press Ltd., 1975), p. 297.

[6]Gagliardi, p. 124.

[7]Emanuel Fthenakis. Manual of Satellite Communications (New York, NY: McGraw-Hill, Inc., 1984), p. 78.

[8]David White (Staff technician, SBS TT&C Site, Castle Rock, Colorado), Telephone conversation, July 12, 1985.

CHAPTER VI

ACCESS METHODS

As satellite systems play an increasingly important role in our national telecommunications networks, they offer the means to quickly restore damaged or destroyed communications to isolated sections of the country. However, the use of different access methods by each system operator presents a major roadblock to interoperability. The particular method used to provide customer access to satellite channels is very important in determining how efficiently satellite transmit power is used. And since the satellite provider is interested in maximizing his profits, he must choose the access method best for his particular requirements and not necessarily compatible with other systems. This chapter will review the fundamental elements of a transponder on a communications satellite and then will discuss the primary multiple access schemes currently in use. Three multiple access methods will be covered: 1) frequency division (FDMA), 2) time division (TDMA), and 3) code division (CDMA) multiple access.

Transponders

The main part of the communications subsystem on a satellite is made up of the satellite transponder and its associated antenna

system. A satellite transponder is quite different from a terrestrial microwave repeater in several respects. For example, many ground stations try to access the transponder at or near the same instant and from many widespread locations. Additionally, the satellite must be capable of accepting and relaying multiple carriers.

Figure 6.1 shows the basic elements of a typical satellite transponder. A bandpass filter separates signals into individual channels. Since the incoming signal is highly noisy and relatively weak, a low noise preamplifier is used to boost it. Next, the signal enters the frequency converter. In this case, single frequency translation is performed, converting the input RF frequency directly into the output RF frequency. The signal then passes through various amplifiers and finally through the traveling wave tube (TWT) amplifier.[1]

The TWT amplifier is a bandwidth limited and a peak-power limited device and becomes nonlinear as it reaches saturation. In a multicarrier system, intermodulation distortion is a significant problem. The multiple carriers that appear at the TWT input can cause large intermodulation products at the output unless the power level is reduced or "backed off." However, the intermodulation and resulting "cross talk" are negligible when a single user accesses the transponder at a given time.[2]

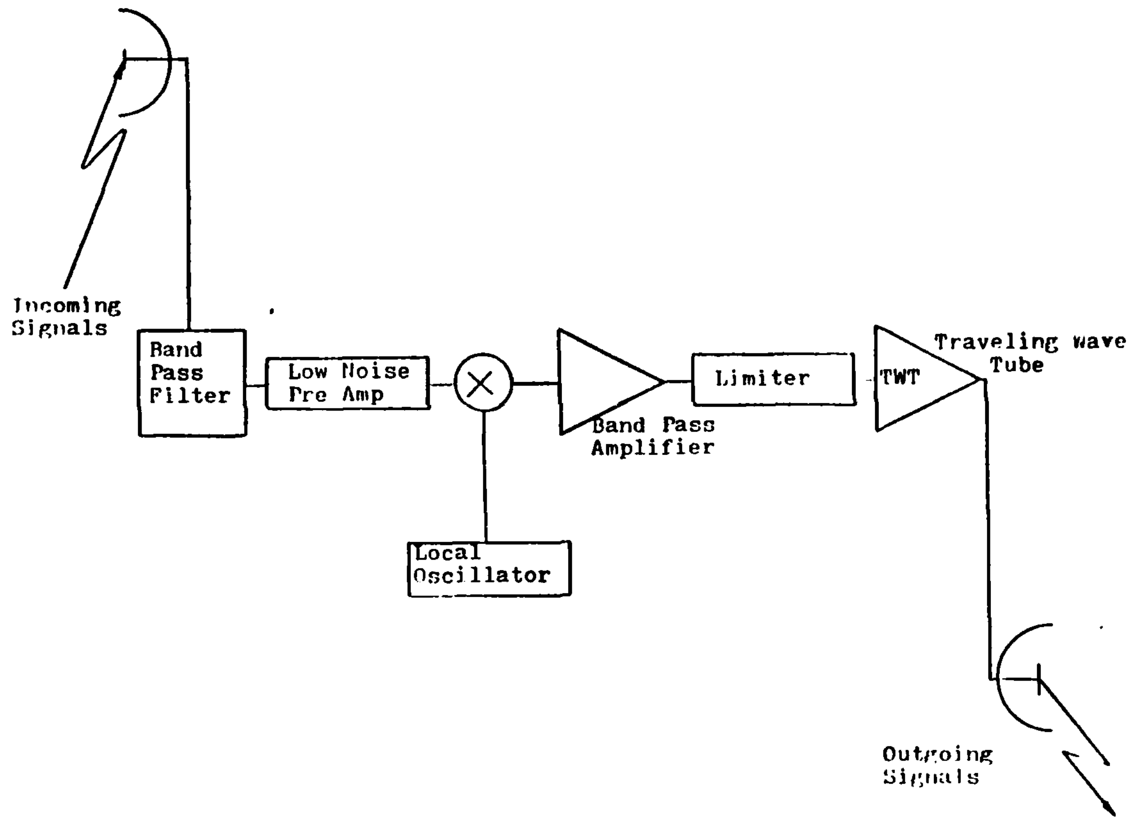


Figure 6.1. Basic Transponder Block Diagram.

Fixed Assignment vs. Demand Assignment Systems

Communications subsystems on satellites can be allocated by either fixed or demand assignment. In fixed assignment, channels are permanently assigned to a particular earth station. No other user may use those channels. This manner of assignment is especially efficient when there are a large number of users on the system and they all carry heavy traffic. However, the efficiency drops off radically when the traffic becomes light. This is because the channels are not available for reassignment to another station that may be experiencing busy-hour traffic. Obviously, if there was a large demand for satellite channels, this manner of assignment would quickly exhaust the available channel capacity of the satellite.

> A major concern of military communication system designers is the development and evaluation of techniques for using satellite channel resources more efficiently. The quality, quantity, and diversity of user demands are increasing rapidly and the current use of essentially dedicated channel assignments will not be adequate to satisfy projected requirements, particularly during periods of military stress. 3

An alternative to fixed assignment is demand assignment. This technique allows a limited number of satellite channels to be shared by a large number of widely scattered earth stations. The channels are assigned on a demand or "as needed" basis and reallocated among many users. In this case, in spite of constantly changing traffic patterns the satellite channels are used efficiently. Demand access can be obtained by either the division of frequency or time of the frequency-time plane. FDMA and TDMA techniques are commonly used for demand assigned systems.

In order to satisfy both types of user requirements, satellites often are able to serve both fixed and demand assignment techniques. In demand assigned systems, the channels are never assigned to a particular pair of earth stations. Therefore, they have a larger traffic-handling capacity than do fixed channels, and as a result handle a larger number of circuits. In a national emergency, with our communications networks damaged over a widespread area, this characteristic of demand assigned systems makes them highly desirable. The government would want to restore communications networks as rapidly as possible and would need the larger traffic-handling capacity of the demand assigned systems. Government agencies would want to communicate quickly with other government groups.

> Access control procedures for allocating satellite channel resources to network users most commonly are based on the use of dedicated channel assignments. As a result, channel utilization is low, satellite power is used inefficiently, and networks are not dynamically adaptive to fluctuations in source statistics and priorities. In addition, satellite channels are susceptible to intentional or inadvertent interference.
>
> The general problem that a system designer must face in seeking to correct these deficiencies is to synthesize and evaluate more effective demand assignment techniques so that preferred approaches for handling traffic with varying characteristics can be identified and implemented. 4

One of these techniques is to provide users with timely access to the satellite channels through frequency division multiple access.

Frequency Division Multiple Access

This is the most commonly used method for multiple access. Since it requires earth station configurations most compatible with the existing terrestrial equipment, FDMA formats are the most popular and were used almost exclusively on early satellites. In its simplest form, each carrier is transmitted at a different frequency. Each signal is given its own frequency channel and interference caused by intermodulation (IM) is reduced through proper frequency selection and reduction of the input power levels allowing linear operation. "Typically, one might reduce the satellite average output power by 50 percent or more (typically 5 dB or higher) to reduce IM products to an acceptable level with a high density of input signals."[5]

Figure 6.2 shows a simplified FDMA format for a single channel in a satellite transponder. Note that the specific format of a frequency channel used for FDMA depends on signal distortion, adjacent channel interference, and intermodulation distortion. Each carrier may transmit a large number of multiplexed signals or it may transmit only one signal such as in a Single Channel Per Carrier (SCPC) system.

The primary disadvantage of FDMA is its susceptibility to crosstalk and intercarrier interference. This interference is minimized through the use of guard bands. However, the wider they are, the less efficiently the allocated frequency band is being used. Larger guard bands are required for larger residual sidebands in each transmitted signal.

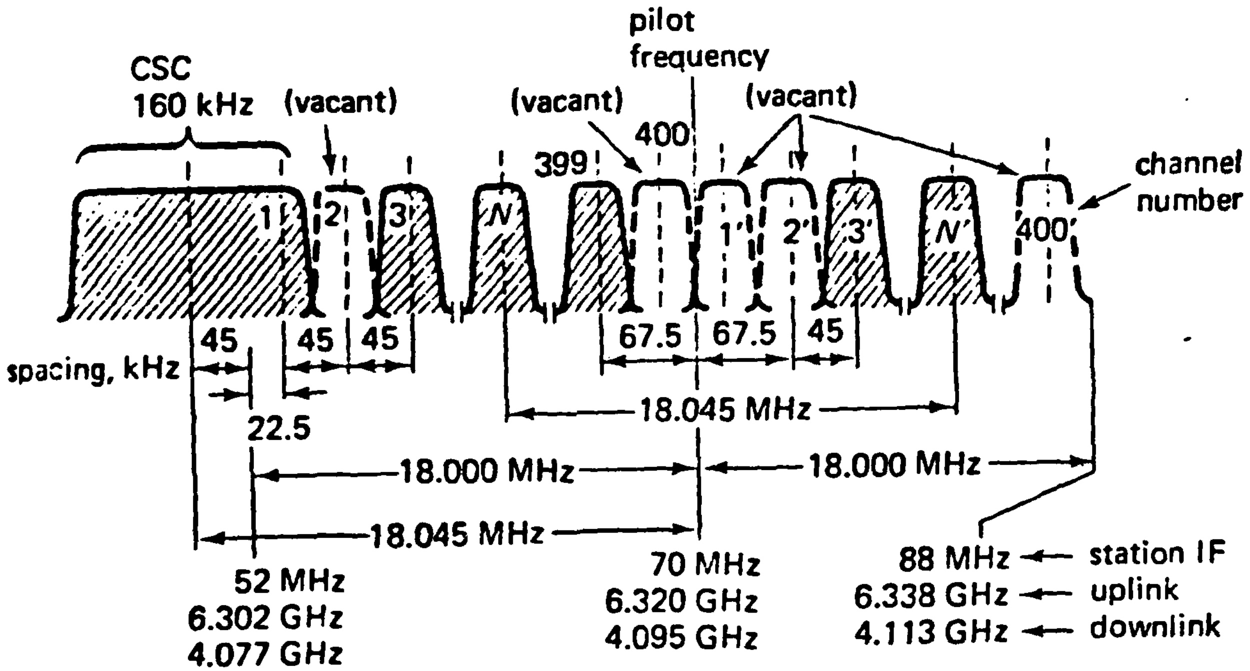


Figure 6.2. SPADE Frequency Assignments: One 36 MHz Transponder.

SOURCE: James J. Spilker, Jr. <u>Digital Communications by Satellite</u> (Englewood Cliffs, NJ: Prentice-Hall, Inc., 1977), p. 219.

Single Channel Per Carrier

Single channel per carrier systems are a subset of the FDMA transmission method. SCPC uses a single voice channel to modulate each carrier. SCPC may be the preferred approach for establishing an emergency communications network by providing a great amount of flexibility. In the first few days after a disaster, government agencies would most likely want to use one voice channel to communicate to a number of different other government groups during each day.

SPADE (Single-channel per carrier, Pulse code modulation, multiple-Access Demand assigned Equipment) is one of the most publicized examples of a demand assignment system used in conjunction with FDMA. The SPADE system was developed by the COMSAT Corporation and is operated by INTELSAT. In the SPADE system, an earth station can use the number of carriers it needs on a dynamic basis in order to handle the traffic demand at any one given instant.[6]

The SPADE system is discussed here merely to provide an example of an SCPC system. It is neither practical nor cost effective to consider INTELSAT terminals for use in restoring our national communications network. Conflicting political and institutional concerns present too many problems to consider using overseas INTELSAT terminals.

Figure 6.2 shows the SPADE frequency spectrum for one of the INTELSAT IV 36 MHz transponders. SPADE uses a single RF carrier for

each 64 kbps digitized voice channel rather than multiplexing a large number of voice channels to form one large-bandwidth signal. The 64 kbps rate comes from a single 4 kHz voice channel sampled at 8000 samples per second with 8 bits representing one sample. QPSK modulation at 32 symbols per second is used with a signal bandwidth of 38 kHz. Channel spacing of 45 kHz is maintained to allow for guard bands of 7 kHz between adjacent channels.[7]

The object of the SPADE system is to provide more efficient service by sharing satellite channels among a number of earth stations. There are 800 individual carriers, each of which represents an access to the satellite, within the 36 MHz bandwidth of a single transponder. PCM coding is used together with QPSK modulation on each carrier.[8] Since a separate carrier is used for each one-way voice circuit, the carrier does not need to be transmitted unless the circuit is actually in use. The channel is voice activated by the user and assigned to him for the duration of his conversation. When he finishes his call, the channel is returned to the common pool and the carrier is once again shut off. This scheme saves satellite power by only using it when a link has been established. "The SPADE system has proved to be more efficient of power and bandwidth per channel than is conventional FDMA or TDMA."[9]

A common signaling channel (CSC) is used by all earth stations in order to monitor the channel assignment status. As calls are initiated and completed, each earth station updates a current log of available frequencies from information provided by the CSC. In

this manner, they are able to determine which channels are free and which are being used. The CSC is a 128 kbps PSK channel which is time-shared by the ground terminals through TDMA.[10]

Time Division Multiple Access

Time division multiple access (TDMA) is the primary alternative to frequency division multiple access. In TDMA, the satellite channels are shared by earth stations, each transmitting its own signal in a specified time slot in a rapid succession of bursts. These bursts are interleaved in the transponder so that they do not interfere with one another. TDMA can achieve efficiencies in satellite power use of 90 percent or more compared to the 3 dB to 6 dB loss in power efficiency of a typical FDMA system.[11] In addition, TDMA does not require the guard bands between each channel as in FDMA. Thus, TDMA is a much more efficient user of available bandwidth. For INTELSAT IV repeaters operating with global beams and a network of ten earth stations with 30-meter antennas and G/T = 41.7, FM/FDMA has typical capacities of 450 one-way voice channels. In contrast, PCM/PSK/TDMA provides 900 channels.[12] The guard times used in TDMA can be kept to a minimum by using accurate timing techniques.

In TDMA each earth station has full use of the entire transponder bandwidth during its prescribed interval of time. Its uplink information alone is processed by the satellite for retransmission on the downlink. As was mentioned in the section above,

FDMA usually requires a 50 percent backoff or reduction in the average satellite output power in order to reduce intermodulation interference. In contrast to FDMA, since only one earth station at a time uses the transponder, all of the earth stations can use the same carrier frequency. Because of this, intermodulation distortion is not a problem and the satellite transponder may be operated at its full power.

However, TDMA is not without its drawbacks. TDMA requires complicated ground operations to insure precision of timing synchronization among the transmitters and receivers. Network synchronization allows them to share the system without interfering with one another. All of the earth stations in the system must be synchronized so that they only transmit during their alloted time period. Because of uncertainty in satellite location, timing accuracies within a fraction of a time slot, on the order of a few microseconds, is extremely difficult and expensive to maintain, but mandatory. The transmission time intervals of each station must be short and regularly repeated. Individually, each ground terminal's activity looks very "bursty." Rapid synchronization must be re-established from one burst to the next. This kind of operation makes TDMA particularly suited to digital operation.

Timing Hierarchy

Figure 6.3 shows the basic layers of the TDMA timing hierarchy. A superframe or masterframe is a number of frames which are

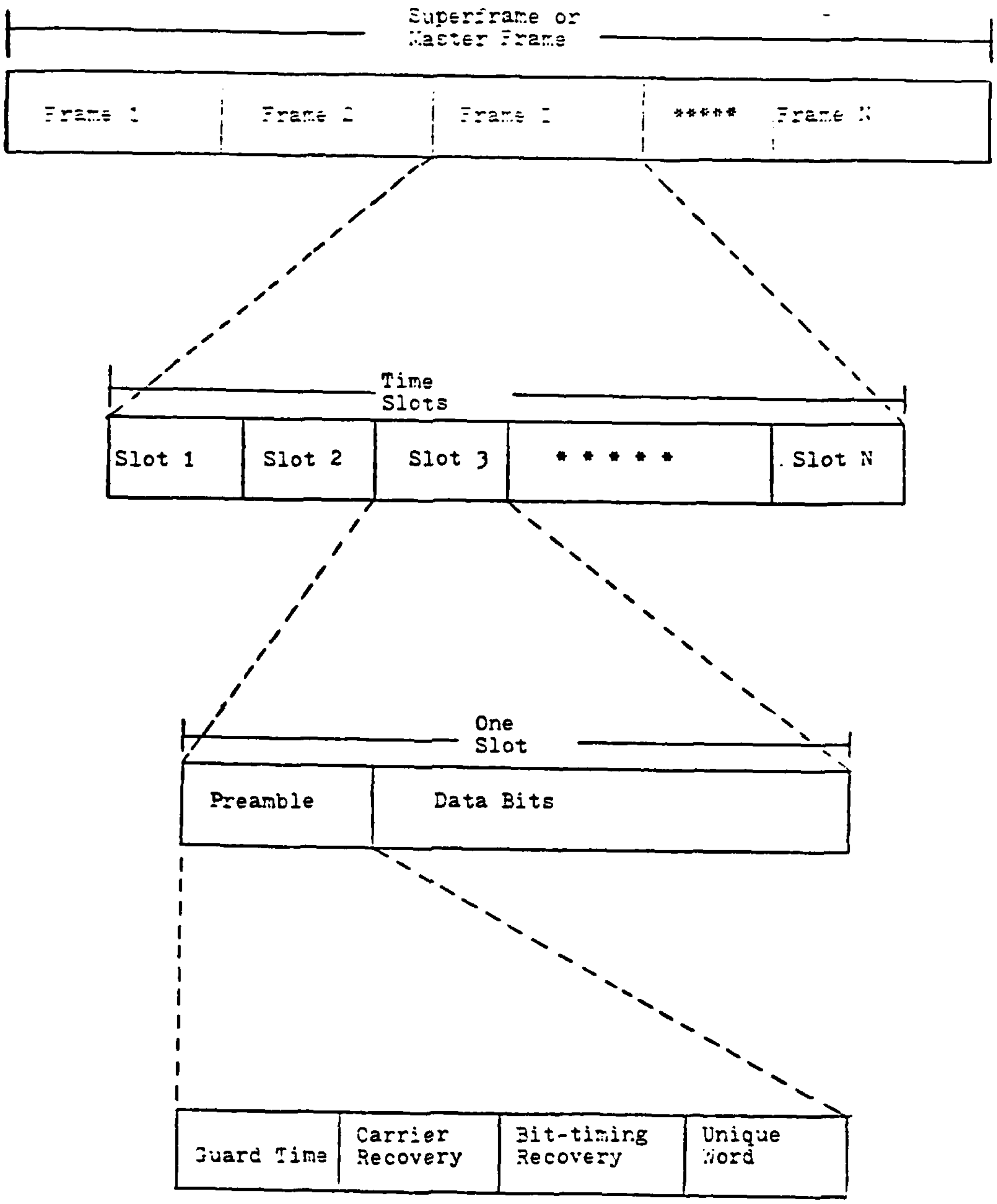


Figure 6.3. TDMA Timing Hierarchy.

organized in a manner to distribute system and network control or signaling information. Each frame is further subdivided into time slots, each assigned to a particular uplink earth station. These time slots are further divided into a preamble time and a data transmission time.

The preamble is used to send a synchronizing waveform to the receiving station so that it can lock up its receiver decoder. The preamble contains guard times, information for clock and timing recovery, the "unique word" which is used to establish word synchronization, a station identification code, and miscellaneous "housekeeping" bits. As mentioned previously, guard times are placed between the slots to prevent overlap. Examples of possible housekeeping information are orderwire for voice or data, signaling symbols, command and control signaling, or error-monitoring bits.[13]

Frame efficiency is defined as:

$$\frac{\text{total number of bits in a frame - overhead bits}}{\text{total number of bits in a frame}}$$

where the overhead bits = guard time bits + preamble bits + reference burst bits. The larger the number of housekeeping bits, the lower the frame efficiency. Frame efficiency is used to make comparisons between different modulation and synchronization schemes and is useful in selecting frame and buffer sizes.

Code Division Multiple Access

"CDMA is also a promising method but may not be capable of providing the efficient use of satellite power or the degree of user signal isolation available with the TDMA approach."[14] In code division multiple access, the separation of frequency and time is unnecessary as in the two previous techniques. Instead, earth stations are identified as pseudo-random (PN) codes which are combined with their uplink carrier waveforms. Each transmitting station uses the full transponder bandwidth and can send its signal whenever it pleases. Each active station's transmission is combined and superimposed on the downlink from the satellite. The receiving stations must know the proper pseudo-random sequence of the transmitter and cross-correlate it with the incoming signal in order to decode the information. CDMA is sometimes referred to as spread spectrum multiple access since the signal is spread over the entire bandwidth. System performance depends on the ability to recognize addresses. This becomes increasingly difficult when the number of active stations becomes large.[15]

The two most widely used methods of CDMA are direct sequence and frequency hopping. In CDMA pseudo-random codes are produced by code generators which provide periodic binary sequences. If a transmitting station's coded address is directly modulated on the carrier, the technique is called <u>direct sequence</u> CDMA. If the address instead changes the frequency of the carrier, the system is called <u>frequency hopped</u> CDMA.

Although CDMA is traditionally assumed to be associated with military applications because of its anti-jam capabilities, commercial users are becoming more interested in applying its characteristics to their fields. CDMA provides users with the ability to minimize interference and combat unauthorized reception, as well as the ability to protect their systems from anti-jam. In addition, CDMA allows for the graceful degradation of a satellite system when the number of users increases and conversely, excess capacity is translated into excess margin when the number of users decreases. New developments in technology have made code generators, correlators, and filters state-of-the-art rather than burdensome.[16] This trend and CDMA's capabilities provides further incentive for satellite operators to move towards increasing the commonality and interoperability of their systems.

A basic spread spectrum system is shown in Figure 6.4. Each satellite customer uses the same carrier frequency and occupies the same RF bandwidth. A spreading function generator (a PN sequence generator for direct sequence and a frequency hopping pattern generator for frequency hopping) is summed with the normal digital signal. This operation acts to spread the digital signal's bandwidth. This resultant signal is then combined with other similar signals. At the receiver, the opposite operation takes place and only the original information on the signal is recovered. The other waveforms appear to a user as a noisy signal with very low power. This is because

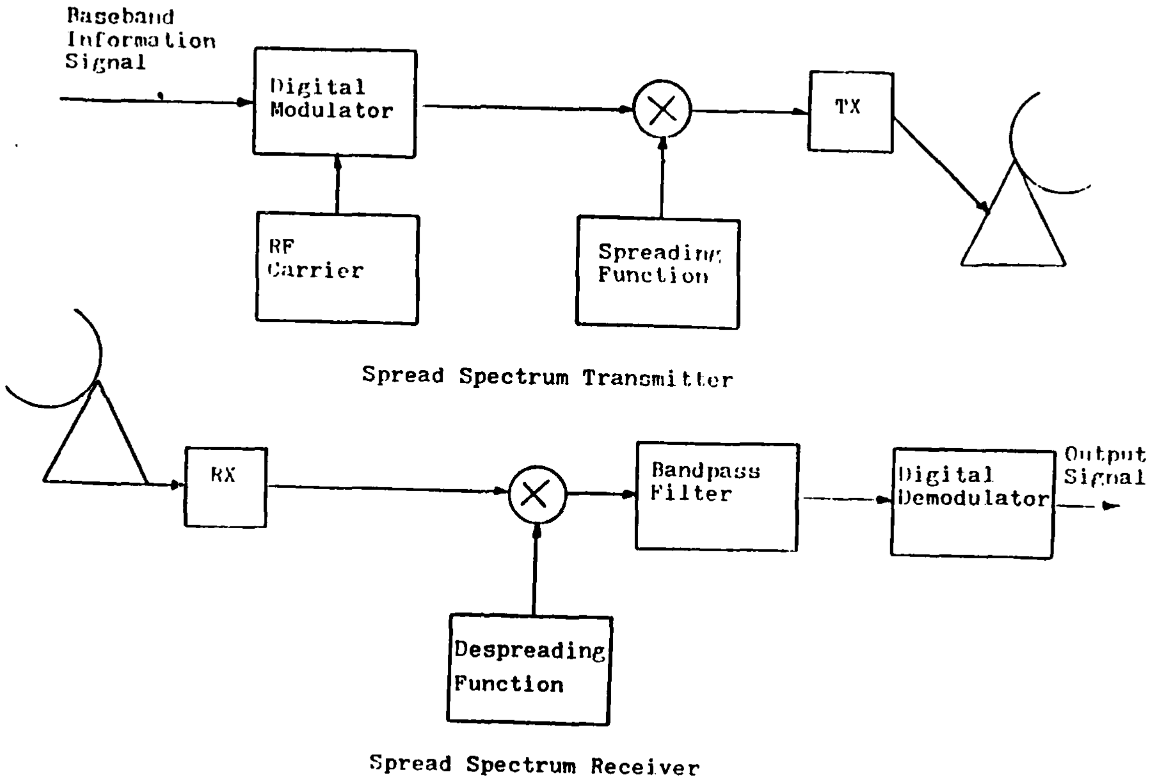


Figure 6.4. Spread Spectrum Block Diagram.

they are not correlated and are effectively spread. Figure 6.5 shows the various power relationships in a spread spectrum system. Notice that for a jammer to be effective, he must raise his overall noise level across the entire bandwidth and at the same time raise his power signal above the desired receive signal.

Direct Sequence Systems

In direct sequence systems, the spreading sequence is added to the information signal before the carrier is phase modulated. The pseudo-random code generator produces a binary sequence at a "chip rate" that is combined with the information signal and then modulated onto a carrier. Phase shift keying (PSK) is used frequently for spread spectrum systems on satellites. The spreading of the bandwidth is determined directly by the chip rate. The larger the chip rate, the greater the spreading and thus the greater amount of interference rejection possible. This quantity is called "processing gain," and is given by:

$$G = \frac{\text{RF Bandwidth}}{\text{Information Bandwidth}}$$

where the information bandwidth = $\dfrac{\text{chip rate}}{\text{information rate}}$.

Typical processing gains given for spread spectrum systems range from 20 to 60 dB. Each earth station forms its PSK carrier in the same manner. Each one uses the RF carrier frequency and the same RF bandwidth, but each has its own PN code.[17]

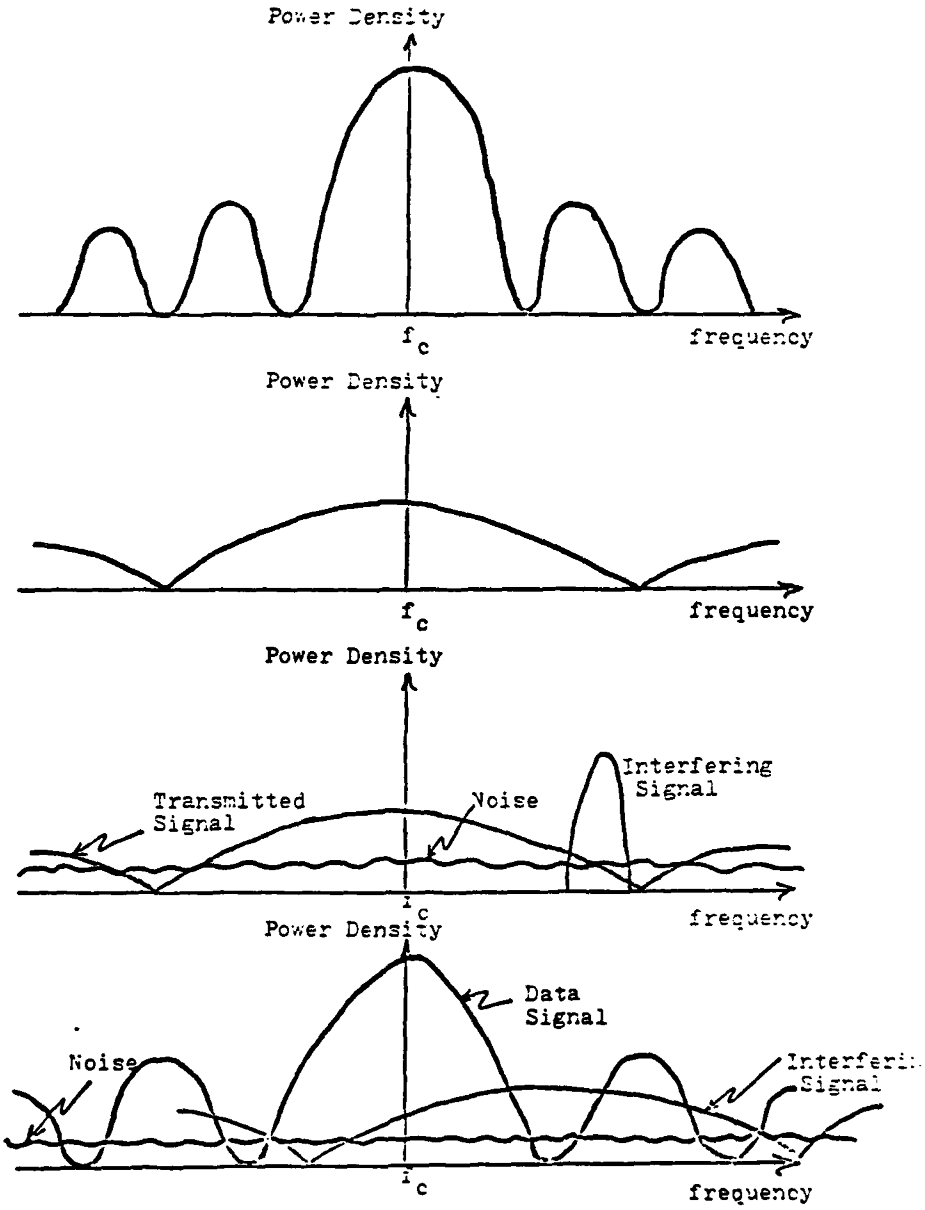


Figure 6.5. Spread Spectrum Power Spectra.

Just as in FDMA, if TWTs are used in the satellite transponder, with a large number of active stations, the result is nonlinear power amplification. As before, this leads to intermodulation distortion. Since the fixed amount of satellite power must be shared, and the intermodulation distortion controlled, the downlink power at the satellite amplifier is backed off. Uplink power control is also necessary so that stronger carrier signals do not block out weaker ones since all stations are transmitting at the same time and on the same RF carrier.

Frequency Hopping

An alternative approach to direct sequence CDMA is Frequency Hopped-CDMA. This method uses a PN sequence to divide the satellite bandwidth into frequency bands and the transmission time into time slots. The PN sequence assigns a particular frequency to each time slot. The transmitter must readjust its carrier frequency for each time slot.

At the transmitter, frequency shift keying is frequently used to modulate the combined PN sequence and information onto the RF carrier. In binary FSK, one of two possible carrier frequencies in each hopping band can be used. The receiver must be synchronized with the transmitter in order to decode the information signal. A code sequence at the receiver is identical to the code sequence which produces the hopping pattern at the transmitter and synchronized with it.[18]

The frequency generators at the transmitter and receiver must be able to accurately and rapidly change frequency over the entire RF bandwidth. Accuracy is essential because any frequency offset of the decoded receive carrier will result in FSK decoding errors. Also, the time needed to hop from one frequency to another must be short. If this time is not kept to a minimum, FSK performance will be degraded by the decoding time lost during the hop transition. The faster the system switches from one frequency to another, the more severe the constraints are on the frequency generators.[19]

Each year more satellites are launched and touted as the panacea to resolving all types of long-distance telecommunications needs. In addition to the proliferation of satellite networks, there are a variety of different access methods. As more and more people want to access these fixed resources, a move away from fixed towards demand assignment systems is becoming popular. If the military is to successfully use commercial satellite networks to quickly restore damaged or destroyed communications to isolated sections of the country, interoperability problems among these access methods must be resolved.

NOTES - CHAPTER VI

[1]James J. Spilker, Jr. Digital Communications by Satellite (Englewood Cliffs, NJ: Prentice-Hall, Inc., 1977), p. 179.

[2]Ibid., p. 182.

[3]H. G. Raymond and J. Kliger. "Demand Assignment Technique for Mixed User Services," AIAA 6th Communications Satellite Systems Conference, April 1976, p. 269.

[4]Ibid., p. 271.

[5]Spilker, p. 215.

[6]Ibid., p. 217.

[7]Ibid., p. 218.

[8]V. K. Bhargava, et al. Digital Communications by Satellite: Modulation, Multiple Access, and Coding (New York, NY: John Wiley & Sons, Inc., 1981), p. 552.

[9]Ibid.

[10]Spilker, p. 219.

[11]Ibid., p. 265.

[12]Bhargava, et al., pp. 229-230.

[13]Ibid., p. 223.

[14]Raymond, p. 274.

[15]Robert M. Gagliardi. Satellite Communications (Belmont, CA: Lifetime Learning Publications, 1984), p. 267.

[16]Bhargava, p. 287.

[17]Ibid., pp. 271-275.

[18]Gagliardi, p. 284.

[19]Ibid., pp. 284-286.

CHAPTER VII

SIGNAL PROCESSING

General

While transponder systems on a satellite are considered transparent to the signals they pass, this is not the case for ground segment equipment. Equipment compatibility problems in earth stations are much more complex. Problems with communications interoperability have evolved because "... commercial satellite systems have been developed to compete in the market place, not in the hostile environment of combat."[1] Commercial satellite vendors have individually optimized their modulation, error coding, scrambling, encryption, and multiplexing techniques to meet performance or cost factors only. If the military is to successfully use commercial satellite networks to quickly restore damaged or destroyed communications to isolated sections of the country, interoperability difficulties between ground station equipment must be resolved.

Modulation

Modulation is the process of encoding signal information on a carrier by varying its amplitude, frequency or phase. In analog modulation, the information is directly modulated from the source onto the carrier. Digital modulation first converts the information into

digital sequences which then are encoded into waveforms for carrier modulation. Most early satellite systems used analog modulation schemes because they were compatible with the existing terrestrial systems. The trend, however, is moving toward digital modulation.

In analog modulation, the modulated carrier takes one of the following waveforms, where m(t) is the information waveform to be transmitted:

Amplitude Modulation:

$$c(t) = A(1 + z_a m(t)) \cos (w_c t + y)$$

Frequency Modulation:

$$c(t) = A \cos (w_c t + 2(pi)z_f \int m(t)dt + y)$$

Phase Modulation:

$$c(t) = A \cos (w_c t + zm(t) + y)$$

In the above formulas, "A" is the carrier amplitude, "w_c" is the carrier frequency in rad/sec., and "y" is the carrier phase angle. The coefficients "z_a," "z_f," and "z" are modulation coefficients which determine the amount of modulation and are referred to as the AM index, frequency-deviation coefficient (in Hz/volt), and phase-deviation coefficient (in rad/volt), respectively. AM, FM, and PM analog carriers are therefore forms of modulated carriers in which the amplitude, frequency, or phase is varied by the information in the input signal.[2]

The important characteristics of a modulated carrier are its bandwidth, the amount of receiver carrier power needed to demodulate,

and the resulting demodulated signal-to-noise ratio. Performance in analog modulation systems is measured in terms of the signal-to-noise ratio of the demodulated information waveform with respect to interference noise. Thus, the larger the SNR figure, the better the quality of the link. The required carrier power is the amount which must be applied to the receiver in order to overcome the noise in the demodulator noise bandwidth, while supplying a carrier-to-noise ratio exceeding a specific threshold. The threshold is set at a high enough level so that distortion of the information waveform is kept to a minimum. Carrier bandwidth is defined as the bandwidth required in the entire RF system to minimize carrier distortion.

FM and PM require more bandwidth than AM, but also achieve a higher demodulated SNR for the same carrier-to-noise ratio. They require more bandwidth than their AM carrier counterparts in order to ensure the greatest use of the available bandwidth and to prevent crosstalk between adjacent FM carriers. FM and PM are the preferred forms of modulation because their constant envelopes are not affected by nonlinear distortion effects as the carriers pass through the satellite. (Nonlinear distortion is covered in a later section.) FM carriers are almost exclusively used in analog modulation satellite systems, while both FM and PM are used in digital systems.[3]

Although modern satellite systems are still mostly analog, digital modulation techniques in satellite systems are rapidly growing in popularity. Compatibility with increasingly digital terrestrial traffic systems makes this trend almost an economic ne-

cessity. Digital modulation and digital buffers are required for compatibility with Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) techniques. In addition, digital formatting makes encryption for communications security and privacy possible.

At the earth station, an analog signal can be converted to a digital signal by a pulse-code modulation (PCM) or delta encoder. The signal passes from the channel encoder to the modulator where it is transformed into an acceptable format for digital transmission. The modulator's output is centered about an intermediate frequency, conventionally 70 MHz, and has a bandwidth proportional to the transmission rate. In digital modulation, input bits modify the amplitude, frequency, or phase of the carrier. The power and bandwidth efficiency of the modulation technique is determined by the process used to modify the carrier.[4]

The modulator's output is "up converted" to RF frequency using a process known as linear translation. The up converter RF output power is then amplified by a high powered amplifier in order to meet the required uplink power. For C-band commercial satellite communications, the uplink RF frequency band is 6 GHz and for Ku-band it is 14 GHz.

"The operation of one company's earth terminal/modem system with another company's system will most likely not be possible due to different TDMA formats and modulation techniques."[5] Additional equipment may have to be provided for the restoration of communica-

tions after a disaster. This additional equipment would be necessary because without it each network station would only be able to communicate with other stations of the same network using the same transponder and the same modulation techniques.

The Commercial Satellite Survivability Task Force suggested several options for increasing the interoperability of earth stations. They would designate several ground terminals as "gateways" and would locate a "standard" modem at each one. These modems might have a 1.544 megabit per second, QPSK (quaternary phase-shift keying), DS-1 format capable of passing 24 voice circuits. Although the costs of providing a standard modem would be borne by the government and would be relatively expensive, this additional equipment would greatly enhance interoperability in the Ku-band.[6]

Error Coding

No data transmission channel is perfect and, thus, errors can be expected to occur in the transmitted information. For voice signals, an occasional error is not a problem because the conversing parties would not notice the omission of a single digitized voice sample. For data, on the other hand, a misplaced bit or digit could seriously misrepresent the information being conveyed. Error correction schemes have been devised to compensate for the occasional errors that are bound to occur, even on relatively reliable channels (bit error rates of 10^{-6} or better).

Because of the time delay inherent in the relatively long transmission path of a satellite channel (over 48,000 miles for a ground-to-satellite-to-ground link), forward error correction techniques are used instead of the more common automatic repeat request method used on terrestrial links. The two basic methods of forward error correction are block and convolutional (or "tree") codes.[7]

In block codes, each data word is converted into a code word of a fixed length independent of the preceding data words. Based on the bits of the source data word, unique bit patterns are added to the transmitted data so that errors can be corrected on the receiving end. Thus, a transmitted block will contain both the original data word and the additional error correction bits. Table 7.1 shows some possible block sizes.

Table 7.1
Block Code Sizes[8]

Data Bits	Error Correction/ Correction Bits	Block Size
1	2	3
4	3	7
11	4	15
26	5	31
1013	10	1033

Convolutional coding involves creating a stream of output bits based each time on the state of the previous source data bits. In particular, the optimal decoding is obtained by means of a Viterbi

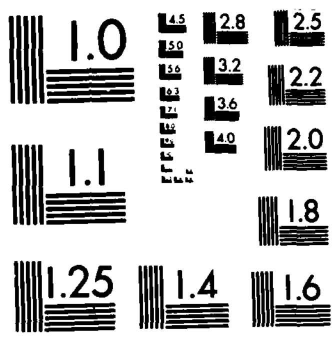
AD-A160 750 A MODEL FOR EVALUATING COMMUNICATIONS SATELLITE INTEROPERABILITY(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH T C GILL 1985 2/2

UNCLASSIFIED AFIT/CI/NR-85-103T F/G 22/2 NL

END

FILMED

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

decoding algorithm and can produce codes with better bit-error performance than previous block codes with the same rate and block length.[9] Although not restricted to this arrangement, a typical Viterbi encoder would output two bits for each bit of the input source word.[10]

Thus, when it comes to forward error correction techniques employed in satellite communications links, there are two main sets of variables. The main variable is the particular technique (block, convolutional, or a variation of either) and the second variable is the size of the output data block. Two earth stations could use a block encoding scheme, but the particular executions of the approach might involve different sized output blocks.

Scrambling

Data scramblers are used to transform data sequences with low transition densities into sequences with strong timing components. Although scrambling devices are similar to encryption equipment, the purpose of scrambling is to prevent the transmission of repetitive data patterns.[11] Scramblers are like encryption devices in that equipment on both ends of the communications link must agree on the scrambling/descrambling process used. Unlike encryption devices, however, the process used is likely to be known in the public domain and possibly even a standard algorithm such as the CCITT V.35 Scrambling/Descrambling standard. According to Bellamy, scrambling is not used on lower rate T-carrier systems such as T1 and T2, but is used on the 274 Mbps T4M transmission links of the former Bell System.[12]

Several options exist for dealing with compatibility between scrambling devices. First, in collecting data on earth stations for the reconstitution data base, sites with like equipment or processes can be identified in which case the processes would be compatible. Secondly, where it can be determined that the source signal will likely have sufficient timing components to preclude the requirement for scrambling, the ability to defeat or bypass the scrambling equipment should be investigated. Finally, including a "standard" scrambler in a standby signal processing unit would eliminate this source of incompatibility.

Encryption

In its simplest sense, encryption is the protection of information through the use of codes and ciphers. In electronic transmission, this protection often involves the manipulation of the source information so that it is unintelligible without the proper decoding algorithm. While the use of information security would probably not be of concern in a civil emergency such as responding to a natural disaster, it is likely that the government would insist on a secure transmission capability when reconstituting in a post-attack environment. In the past, the U.S. government has employed encryption devices developed by, or under the auspices of, the National Security Agency. However, the use of these government devices presents a number of problems when being considered for use in a private sector-based satellite communications system.

The two basic problems are electronic compatibility and protection of the cryptographic hardware and codes against unauthorized disclosure. Government cryptographic equipment, for the most part, has been designed to operate with systems designed to government specifications. These specifications, primarily military standards, are likely to differ significantly from those used to design and deploy commercial communications systems. Since there is, in fact, a "family" of government equipment, it will take a careful analysis of the specifications of the government devices and the potential commercial earth stations in which they might be employed to determine which devices might be used to provide secure communications.

In addition to the problem of electronic compatibility, the issue of storage and protection of government cryptographic equipment and codes is significant. It is somewhat unlikely that private-sector communications facilities can provide the degree of security required by government regulations. Further, the commercial sector will understandably be reluctant to accept the sizeable responsibility that goes with handling government cryptographic equipment.

At least two possible approaches exist to this issue. In cases where it has been determined that government cryptographic equipment will operate with particular commercial systems, the equipment could be deployed from authorized government storage locations by government personnel who are authorized access to them in the normal course of their duties. These same personnel could operate, maintain, and protect the cryptographic assets at the private-sector

terminals. This option would require significant planning and coordination between government personnel and the owner/operators of commercial satellite earth stations.

Another alternative for providing secure communications over satellite links is the use of the Digital Encryption Standard (DES). DES was designed primarily for use in the private sector and may already be in use in some of the terminals the government might use in a reconstituted communications system. A procedure might be devised where a government-controlled code could be used in DES equipment located at commercial communications sites. In any case, the issue of secure government communications over commercial facilities is one where the administrative concerns of protection against disclosure are likely to be more difficult to resolve than the technical questions involved.

Multiplexing

Since a satellite has a capacity and digital throughput larger than any one subscriber can use, multiplexing divides its capacity into channels which can be used independently. Multiplexing is the process of combining two or more signals together and sharing a common path. Three types of multiplexing are of interest: 1) frequency division, 2) time division, and 3) code division multiplexing. In addition, there are several other forms such as space division and polarization multiplexing. Space division multiplexing can be best described as running a separate physical path for each signal. For

instance, in a conduit you may have a bundle of wires, each of which carries only one signal. Polarization multiplexing involves separating signals from each other through their different horizontal or vertical polarities. These forms of multiplexing will not be covered any further in this discussion.

Frequency division, time division, and code division multiplexing are the types most prevalent in communications systems. Frequency division multiplexing occurs when signals occupying nonoverlapping frequency bands are combined and a single, desired frequency is recovered through filtering. In time division multiplexing, signals are combined into composite, high-speed bursts of nonoverlapping time slots. A desired signal is selected from the composite by choosing the proper time slot which is obtained by using timing references. In code division multiplexing, signals are combined with codes that give them a unique signature before they are combined in the time-frequency domain. These signals are generally digital. They are demultiplexed through cross correlation with a predetermined reference signal.[13]

These forms of multiplexing enable us to combine signals together in order to share a common medium and to operate our communications systems more efficiently. However, the proliferation of FDM systems and the trend toward digital TDM systems makes even multiplexing a compatibility issue. These two technologies work within their own networks well enough, but are not interoperable with each other.

Conclusion

Because of the number of variables involved in the signal processing functions of an earth station, all of which must operate in concert to intelligibly transmit information from one end of a link to another, it may be found that very few terminals not designed to operate together will do so without major modification. A more feasible approach may be to study the possiblity of installing standard, government-provided signal processing equipment as a back-up channel in selected earth stations. To reduce both cost and lead time, commercial, off-the-shelf equipment should probably be used. After a comprehensive survey of the commercial equipment already in use in earth terminals, it might be found that a certain degree of compatible equipment already exists so that a lower level procurement could take place to provide additional compatible earth stations.

NOTES - CHAPTER VII

[1]Fred E. Bond. "Systematic Approach for Commercial Satellite Communications Survivability," August 3, 1984, p. 4.

[2]Robert M. Gagliardi. Satellite Communications (Belmont, CA: Lifetime Learning Publications, 1984), pp. 26-27.

[3]Ibid., p. 31.

[4]V. K. Bhargava, et al. Digital Communications by Satellite: Modulation, Multiple Access, and Coding (New York, NY: John Wiley & Sons, Inc., 1981), p. 19.

[5]Commercial Satellite Communications Survivability Report, May 20, 1983. Prepared by the CSS Task Force Resource Enhancements Working Group, p. 3-2.

[6]Ibid.

[7]James Martin. Communications Satellite Systems (Englewood Cliffs, NJ: Prentice-Hall, Inc., 1978), p. 268.

[8]Ibid., p. 269.

[9]Gagliardi, p. 63.

[10]Harry L. Van Trees, ed. Satellite Communications (New York, NY: IEEE Press, 1979), p. 276.

[11]John Bellamy. Digital Telephony (New York, NY: John Wiley & Sons, Inc., 1982), p. 168.

[12]Ibid.

[13]Bhargava, et al., p. 22.

CHAPTER VIII

NUCLEAR EFFECTS

Our national nuclear weapons and strategic defense policy is founded on the principle of deterrence. This deterrent posture no longer relies solely on the idea of the threat of massive retaliation on Soviet cities. Instead, defense specialists employ the idea of flexible response. "They envision the possibility of a nuclear war that would be escalated and fought in controlled stages while the U.S. sought to negotiate an end to the conflict."[1]

Caspar W. Weinberger's Annual Statement for Fiscal Year 1983 stated that the United States must possess the means "... to impose termination of a major war on terms favorable to the United States and our allies even if nuclear weapons have been used."[2] If hostilities did break out, the chances of halting a disastrous escalation might rest on the ability of the two superpowers to maintain their flow of intelligence information and communications from satellites. The concept of a lengthy nuclear war necessarily requires that a coherent command, control, and communications network remain in operation for many weeks.

Defense strategies make the assumption that if the nation is attacked, the President and senior commanders will be able to issue orders to insure retaliation. These orders will only be relayed to

the weapons sites if some of the nation's communications facilities survive. It is impossible to provide a foolproof system to maintain the communications link between the President and the nuclear strike forces, but it is possible to add redundancy and enhance those facilities that do exist.

Nuclear Vulnerabilities

This paper has made an argument for finding ways to implement an interoperable network of commercial communications satellites in order to augment our national security/emergency preparedness communications network. However, this satellite network will be of little use if it cannot operate in a nuclear scenario. In a nuclear-charged atmosphere, satellite signals are vulnerable to the effects caused by nuclear explosions. For instance, a high-altitude nuclear blast would result in the "blackout" effect which would be particularly devastating for lower frequencies. Electromagnetic-pulse (EMP) effects could disrupt enough electronic equipment that most communications and computer systems would not work.[3] And, microscopic dust and smoke particles caused by ground bursts directed against hardened targets would fill the air with dust and smoke particles, effectively blocking the transmission of satellite signals.

RF Blackout Effect

High-altitude nuclear bursts and radioactive clouds from lower-altitude bursts would increase the electron density in the

lower layer of the atmosphere. HF frequencies would have trouble penetrating the lower ionosphere and refracting back to earth in a nuclear-charged atmosphere. This lower layer would contain a high density of ions and neutral atoms, and HF signals passing through this layer would be absorbed. This absorption is known as the "blackout" effect and could last for extended periods.[4]

The same phenomenon would also cause UHF satellite signals to undergo absorption. The absorption coefficient is inversely proportional to the square of the radio frequency.[5] Therefore, EHF and SHF signals would be the least affected. However, even these frequencies are not immune to the effects of a nuclear-charged atmosphere. They are vulnerable to transient interruptions known as scintillations. These interruptions are generated at the receiving equipment when parts of the signal wave front arrive out of phase and interfere with one another. These out-of-phase conditions occur when the signal passes through regions of different electron density caused by a nuclear detonation.

Electromagnetic Pulse Effects

Electromagnetic pulse is another form of interference. It is caused by gamma rays which are generated when a high-altitude burst creates intense electrical currents in the upper atmosphere. These gamma rays contain frequencies across the entire RF spectrum from extremely low frequency (ELF) to very high frequency (VHF). A single high-altitude nuclear detonation at an altitude of several hundred

kilometers could disrupt communications across the entire United States.[6] EMP disrupts communications equipment in a variety of ways by creating violent voltage surges damaging sensitive solid state devices. EMP develops high energy very rapidly: 11 kiloamperes in less than one microsecond.[7] EMP enters communications equipment through antenna systems and power lines.

At least one-half the energy yield of most nuclear weapons is generated by fission and the rest is generated by fusion. In a nuclear detonation, the fission process produces atoms in an unstable isotopic state. Alpha, beta, and gamma radiation is released during the radioactive decay of these states. Gamma rays and neutrons make up about 1 percent of the nuclear weapon's total energy.[8] Approximately 300 unique radiative isotopes are produced as a result of an explosion.[9]

Gamma rays interact with the atmosphere and produce electrons and positive ions. This flow of electrons causes a current of electromagnetic energy to radiate. Thus, a small portion of the nuclear energy is transformed into energy components in the RF electromagnetic spectrum. Severel EMP effects can be expected to range over large areas. EMP exposure can cause electronic components to burn out and can disrupt digital processing. The prevalent use of solid state technology in present satellite systems and electronic equipment makes them "significantly more susceptible" to EMP effects than early satellite systems.[10]

EMP produced by a high-altitude burst (outside the atmosphere) can severely damage satellites. Two important means of protecting satellites from these hazards are equipment hardening and reconstitution.[11] Hardening is accomplished by protecting electronic equipment beginning with the design stages. System design to combat EMP effects might include the following: Shielding, electrical bonding, cable/wire bundling, filtering, surge suppression, component selection, circuit design, and grounding.[12] The CSS Task Force supported the idea of a generally hardened, spread out, numerous commercial satellite base as providing the best overall protection of the space segment.[13]

Reconstitution of a satellite system is accomplished by replacement of damaged equipment. These spares are to be stored in EMP protected areas. Earth station reconstitution can be accomplished through the use of ground mobile satellite terminals. However, reconstitution of the space segment was rejected by the CSS Task Force because of the unacceptable amount of time required to restore commercial satellite service. Full restoration is estimated to take from five to ten years.[14] Launch vehicles would be either damaged completely or unavailable. The cost of replicating a full complement of satellites is enormous and considered unacceptable. Storing unprotected satellites in space as spares was also rejected because this provides little or no protection against a nuclear detonation.

Dust and Smoke

In a widespread nuclear exchange, ground-based communications facilities and control centers would be highly vulnerable to attack. Ground bursts would be targeted against hardened targets, such as missile silos and command and control centers. Air bursts would be aimed at soft targets. Soviet targeting strategy calls for a handful of missiles to hit key communications links such as satellite relay stations to prevent the United States from launching a coordinated retaliatory strike.[15]

There are more than 1,000 missile silos in the U.S. strategic arsenal and the Russians probably have at least two warheads committed to each one. In the same light, there are about 1,400 missile silos in the Soviet Union which are targeted by U.S. warheads.[16] Ground bursts may be additionally targeted against such strategic targets as: air bases, command and control facilities, and communications nodes.

> In short, it seems quite possible that at least 4,000 megatons of high yield weapons might be detonated at or near ground level even in a war in which cities were not targeted, and that roughly 120 million tons of submicrometer soil particles could be injected into the stratosphere in the North Temperate Zone. 17

Satellites which survive would be of questionable use because of the confusion caused on the ground by a strategic nuclear exchange. Within the target zones, it would be too dark to see, let alone communicate effectively among the remaining earth stations and

their satellites. The huge amount of smoke and dust in the atmosphere would drastically attenuate the signals.

How Much and How Long

How much will satellite signals be attenuated by RF absorption and by dust and smoke? How long will these systems remain unusable? These questions are important to answer, but a quantitative analysis is very difficult to provide because of the many unknown factors involved in the detonation of a nuclear weapon. These factors include, but are not limited to, the time of day, time of year, altitude, number, yield, and combination of weapons exploded. The RF propagation problem is extremely complex and includes phase shifts, refraction, reflection, and others, including changes in skip distances and signal delays. Little data on actual nuclear burst effects on RF propagation are available, and no tests will be conducted or are planned under the existing nuclear test moratorium.

Therefore, RF propagation and link survivability can only be tested in the laboratory using analytical techniques. Wescom uses computer programs to assess nuclear effects on satellite communications signals. Their program uses input data such as the ground station locations, transmitter and receiver, nuclear weapon data, burst location, ground station transmitter/receiver, operating characteristics, and antenna patterns. The program models the physics creating the complex ionization conditions and predicts their effect on RF propagation. The output is in the form of an estimated bit

error rate or message error rate. Obviously, this analytical task is very complicated and the results are only as accurate as the models used to predict the ionization and debris produced by the explosion.[18]

The Commercial Satellite Survivability Task Force states that the detonation in the exoatmosphere, an altitude above 80 kilometers, presents the largest threat to satellite communications. The detonation creates a plasma which is made up of nuclear fuel, bomb case debris, delivery vehicle, and residual atmosphere. A bubble is created by the plasma in the magnetic field of the earth which confines debris. The debris emits electrons or beta decay particles. The high energy electrons are trapped in the magnetic field and create an artificial radiation belt. The intensity and range of this belt are dependent on the yield, design, altitude of detonation, and the latitude of the burst. "The belt is completely formed in 6 hours and then starts to decay, lasting on the order of months to years and is superimposed on the natural radiation belts."[19]

The problems a nuclear-charged atmosphere pose for satellites and other electrical equipment point out the difficulty the nation has maintaining a viable communications network to carry out its nuclear weapons and strategic defense policy. Our strategic defense communications systems must be able to withstand the effects of disruption by EMP effects and disturbance of the ionosphere. In this paper, we have proposed linking all existing commercial satellite systems together as one means for increasing the survivability of our

national security/emergency preparedness network. By spreading our resources across the nation, the chances for striking a decapitating blow are significantly reduced. Redundancy and diversification may not be the optimal solution, but it is a plausible one and well within our near-term technical capabilities.

NOTES - CHAPTER VIII

[1]Jonathan Tasini. "Are We Sitting Ducks in a Nuclear War?" Business Week, July 8, 1985, pp. 12-13.

[2]Ashton B. Carter. "The Command and Control of Nuclear War," Scientific American, January 1985, p. 32.

[3]Ibid., pp. 32-34.

[4]Ibid., p. 37.

[5]Ibid.

[6]Ibid., p. 38.

[7]W. G. Kuller and D. W. Hanifen, "Space System Survivability," Laser and Laser Systems Reliability, Proceedings of SPIE - The International Society for Optical Engineering, Vol. 328, January 28-29, 1982, p. 77.

[8]Commercial Satellite Communications Survivability Report, May 20, 1983. Prepared by the CSS Task Force Resource Enhancements Working Group, p. H-3.

[9]Richard P. Turco, et al. "The Climatic Effects of Nuclear War," Scientific American, August 1984, p. 39.

[10]Survivability Report, p. G-2.

[11]Ibid.

[12]Norman J. Rudie. Principles and Techniques of Radiation Hardening, Vol. 1 (North Hollywood, CA: Western Periodicals Company, 1980), p. 1.18.

[13]Survivability Report, p. G-3.

[14]Ibid., p. G-2.

[15]"Book Targets Pentagon's Command, Control System," Boulder (Colorado) Daily Camera, May 17, 1985, p. 14B.

[16]Climatic Effects, p. 38.

[17] Ibid.

[18] Edwin Smith. "Nuclear Effects on RF Propagation," Defense Electronics, October 1984, p. 232.

[19] Survivability Report, pp. H-5 - H-6.

CHAPTER IX

OTHER CONSIDERATIONS

Restoration and Control

Those government officials who need access to the network must be reasonably assured that they will have it. If the remaining communications networks are jammed with nonessential calls, they will be denied timely access. Some form of an emergency communications network must be reconstituted in an orderly and predetermined manner. In an attempt to move toward this goal, President Reagan signed Executive Order 12472 on April 3, 1984, formally establishing the National Communications System (NCS) as the single focal point for joint industry-government national security and emergency preparedness telecommunications planning. The NCS mission

> ... shall be to assist ... in the coordination of the planning for and provision of national security and emergency preparedness communications for the Federal government under all circumstances, including crisis or emergency, attack, recovery, and reconstitution. 1

Communications Focal Point

The NCS serves as a focal point for joint industry-government national security and emergency preparedness telecommunications planning. To assist the NCS in accomplishing its goals, it established a joint industry-government National Coordinating Center (NCC) which is

capable of assisting in the initiation, coordination, and reconstitution of national security and emergency preparedness telecommunications services or facilities under all conditions of crisis or emergency. The NCC is jointly staffed around the clock by representatives of the government and selected members of the telecommunications industry. With the breakup of AT&T, and no nationalized communications network run by a single entity, the role of the NCC has become increasingly important.

A federal agency such as the NCC is necessary to coordinate the plans and procedures necessary before and during a national emergency in order to facilitate the reconstitution of our national communications network. The manager of the National Security Council is responsible for developing these

> ... plans and procedures for the management, allocation, and use, including the establishment of priorities or preferences, of Federally owned or leased telecommunications assets under all conditions of crisis or emergency. 2

Any attempt at tying a fragmented network back together without a central federal authority would be chaotic. Before an emergency evolves, plans must be completed and coordinated so that each civilian company and government agency knows and understands its role. Without this pre-planning, individual carriers would not know which systems, and in what order, to tie together.

Restoration

The restoration of satellite communications is only one piece of the overall network that the NCS must be concerned with. Restoral of these systems must necessarily fit within the requirements of the total national telecommunications network. Plans and procedures developed to satisfy these requirements would give guidelines to test NCC network restoral procedures for satellite systems. The NCC's establishment of a data base listing the capabilities of the nation's satellites would be a key part of the restoration capability. Emergency communications procedures are needed between the NCC and the satellite earth stations and control facilities. An intersite, universal satellite station orderwire would be one possible means for providing the necessary coordination. In addition, each site would develop its own emergency operation plans for the restoral of communications in response to NCC direction.[3]

System Control

Once a viable communications network has been reconstituted, the next apparent problem is controlling who should use it and when. President Reagan's Executive Order, referred to above, states that the

> NCS shall seek to ensure that a national telecommunications infrastructure is developed which is capable of satisfying priority (emphasis added) telecommunications requirements under all circumstances through the use of commercial, government and privately owned telecommunications resources. 4

If everyone attempted to access the system at the same time, no one would complete their call.

This problem can be corrected by establishing a "priority" system similar to the one currently in use in the Defense Communications System (DCS). The DCS is the general purpose Department of Defense communications network which consists of government-owned and leased transmission media, relay stations, and switching centers. The system provides service to its customers through common user switched networks such as AUTOVON, AUTODIN, and AUTOSEVOCOM. Each of these networks has a military precedence system and provides service to a large community of Department of Defense and other U.S. Government users. In addition, the DCS provides high-priority customers with special services, allowing immediate responsive command and control communications capabilities.[5] The priority system allows use of a network not on a "first-come-first-served basis," but on a "need" basis. In other words, a high-priority user would be able to preempt or block a lower user's call.

In a telephone interview with Mr. George F. H. Silbermann, National Security Agency representative to the National Communications System, he stated that at the present time, the NCS does not have a preemption protocol/signaling format in place. However, these protocols are being established under a project called the Telecommunications Service Priority (TSP) system. The TSP is being jointly developed by representatives from both industry and the government. The NCS staff is coordinating the effort and channeling inputs from

the Federal Communications Commission, equipment manufacturers, and the long-distance carriers in order to come up with a workable solution by 1987.[6]

The TSP Task Force is meeting once a month in order to establish a system that will be able to respond to different national security situations with predetermined categories of users with their priorities already assigned. The FCC and industry representatives are on the task force because once the requirements have been established, the manufacturers and carriers will be obligated to meet them. The FCC is expected to issue a rulemaking next year.

The NCS has established a set of twelve requirements for the TSP. One of the requirements states that a priority system must recognize a priority customer anywhere in the country. For example, a customer must be able to go to a phone booth and establish his priority. Another requirement states that the protocols must be applicable to the entire system. They must work from the customer premise terminal equipment from one end to the other, not just through the long-distance transmission system. One possible solution might be to establish protocol interoperability at central locations.

At major communications nodes, "gateway" stations could be established. These gateways would allow communications from one network to cross over to another system. Subscribers from one network would then have access to those in the other system. Multiple entry points of up to twenty of these gateways would greatly enhance interoperability and survivability. The ability to obtain preemption

capability through the DCS would be possible with DCS connectivity at these gateway stations. The existing commercial networks are not capable of recognizing Department of Defense protocols. Provisions must be made for one system to accept the capabilities of the other and an identical set of signaling formats and preemption protocols would be required in order to make this preemption capability possible.[7]

The precedence hierarchy must be established prior to its use in order to alleviate confusion. In order for the NCS to make sure that their planning is adequate, they are able to develop and activate test and exercise programs. These programs are designed to evaluate the capability of the Nation's telecommunications resources to meet national security and emergency preparedness telecommunications requirements.

NOTES - CHAPTER IX

[1]Ronald Reagan, Executive Order 12472 of April 3, 1984, Assignment of National Security and Emergency Preparedness Telecommunications Functions.

[2]Ibid.

[3]Commercial Satellite Communications Survivability Report, May 20, 1983. Prepared by the CSS Task Force Enhancements Working Group, pp. 32-33.

[4]Reagan.

[5]Gilbert E. LaVean. "Interoperability in Defense Communications," IEEE Transactions on Communications, Vol. Comm-28, No. 9, September 1980, p. 1453.

[6]George F. H. Silbermann, National Security Agency representative to the National Communications System, Telephone interview, July 17, 1985.

[7]LaVean, pp. 1448-1450.

CHAPTER X

SUMMARY AND CONCLUSIONS

The Developed Interoperability Model

In order to determine the degree of interoperability of two or more satellite earth stations, a wide range of terminal design variables must be compared. Each stage of the signal processing and transmission path offers a variety of options likely to be employed in a large number of variations. The model developed in this paper and summarized below presents a systematic means of determining the degree to which two earth stations might be able to communicate with each other. On a fairly modest scale, the model simply requires collecting the appropriate data on candidate earth stations, comparing the elements that must agree or complement each other, and, when a probable match is found, calculating a number of parameters required to actually establish the link. At best, however, the model can only indicate the theoretical success of a given link. Where feasible, on-site testing to verify the results indicated by the initial data matches would be highly desirable.

The model requires two basic sets of data: one set on the domestic satellites in orbit along the geosynchronous arc accessible from the United States and another set on the earth stations that will be trying to communicate via the satellites. Effectively, three

matches must take place: (1) earth station-to-satellite uplink; (2) satellite-to-earth station downlink, and (3) earth station-to-earth station signal processing. Figures 10.1 and 10.2 present the data required to perform matches.

Once the data in the two figures have been collected and correlated, a report should be generated that would indicate all possible accessible transponders to the earth station along with the resulting parameters for each link (elevation angle, azimuth, signal level, etc.). In addition, the report should list all other earth stations which are likely to be compatible.

The data represented in Figures 10.1 and 10.2 are probably the minimum required to determine potential interoperability. Additional data may help refine the model and actual on-site testing may be required to confirm that a link can, in fact, be established. This would be especially true for links where the preliminary analysis indicated marginal signal strength.

Conclusions

Because the telecommunications systems of the United States are not a nationalized utility, the Federal Government must acquire the communications capability it requires from private commercial entities. Those firms have developed an extensive satellite communications capability and it is only logical that the Federal Government make use of it to meet its emergency communications needs. To do so, however, will require a great deal of planning, testing,

Satellite:________________ Owner:________________

Orbital Position (longitude):____________

	Uplink		Downlink	
Trans-ponder	Frequency/ Polarization	G/T	Frequency/ Polarization	EIRP
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23				
24				

Coverage patterns:

Figure 10.1. Required Satellite Data.

Owner/Operator:______________________________
Address:______________________________
Latitude:______________ Longitude:______________
Site Elevation:______________ Rain Region:______________

Antenna Data
Size:______________ Polarization:______________
Coverage of Geosynchronous Arc:______________
Angles Obstructed:______________
Potential Interference:
Direction:______________ Frequency:______________
Tracking Capability:______________

Transmitter
EIRP:______________
Frequency:
Primary:______________
Upper Limit:______________
Lower Limit:______________

Receiver
G/T:______________
Frequency:
Primary:______________
Upper Limit:______________
Lower Limit:______________

Signal Processing
Access Method:______________
Modulation Method:______________
Error Coding Method:______________
Scrambling Method:______________
Encryption Method:______________
Multiplexing Method:______________

Primary station application:
Voice:__________
Data:__________
Video:__________
Other:__________
Time Manned:______________
Emergency Power:______________

Terrestrial Connectivity:

Figure 10.2. Required Earth Station Data.

and negotiating between the parties involved to ensure the required capability is available when needed.

Unless the concern over satellite system interoperability is only academic, the Federal Government should first define as precisely as possible what its emergency communications requirements are. In this way, the required effort and funding can be focused where it will do the most good. In all likelihood, the requirements will be given priorities to be dealt with incrementally. It is possible, however, to perform a general analysis that could support emergency preparedness planning for a variety of scenarios.

Knowing the relationships of the variables of the model developed in this paper, a relatively straightforward computer program should be written to process the appropriate information collected in a data base. The program should identify possible earth station matches, perform link analyses, and construct hypothetical networks based on its findings. Depending on the nature of the emergency, the program should also reconstruct new networks based on inputs of inoperative nodes.

Following development of the program, a comprehensive data collection effort is required to gather the required information on as many domestic satellites and earth stations as possible. The survey should be as comprehensive as possible because it would be extremely difficult to predict which assets would survive in a variety of emergency situations. To protect the proprietary nature of some of the data involved, the government will probably have to guarantee

adequate information security on behalf of the private sector participants.

If an insufficient level of interoperability is found to exist to provide the capability required, the government should consider providing a standard rack of signal processing equipment to key earth stations. These federally procured assets would serve as an emergency backup capability. Assuming that the technical requirements for such equipment need not exceed those of commercial systems already in use, the government could avoid excessive costs and lead time by buying commercial, "off-the-shelf" equipment. If the equipment was inexpensive enough, such a program could be conducted on a fairly wide-scale basis. A variation on this approach would be to procure and hold the assets for deployment to predetermined locations.

The problems a nuclear-charged atmosphere pose for satellites and other electrical equipment point out the difficulty the nation has maintaining a viable communications network to carry out its nuclear weapons and strategic defense policy. One key issue, it appears, is that based on the available data, if a nuclear weapon is exploded in the upper atmosphere, the decay from radioactive particles could last on the order of months to years, making even an interoperable satellite system unusable at worst and crippled at best. In this paper, we have proposed linking all existing commercial satellite systems together as one means for increasing the survivability of our national security/emergency preparedness net-

work. By spreading our resources across the nation, the chances for striking a decapitating blow are significantly reduced. Redundancy and diversification may not be the optimal solution, but it is a plausible one and well within our near-term technical capabilities.

An enduring, interoperable satellite communications system should resist all but a heavy, deliberate nuclear attack without serious damage. The operational functions the system can carry out depend on the potential scale of attack and how long the capability can be kept coherent. The critical question in assessing the system is, how long to do it? Short-term endurance to ensure the positive control of weapons and selective retaliation is a feasible goal for a robust, interoperable satellite network. Long-term endurance and reliability in a large-scale nuclear exchange are impossible to achieve because nuclear devastation of the environment due to the climatic phenomena detailed in Chapter VIII and because communications facilities would probably be heavily targeted in this kind of attack. However, in order to deter large-scale attacks, only an assured retaliatory capability is needed, not an enduring one. Our goal is to provide this capability through a robust, interoperable system of commercial communications satellites.

In the final analysis, it appears that the whole question of achieving satellite system interoperability in support of government emergency communications is not so much of a technical one as it is a regulatory and funding one. It will take a great deal of cooperation between government and industry to provide the necessary communica-

tions capability. If the early experiences of the NSTAC process are any indication, the required cooperation can take place on a level that will provide the Federal Government with the emergency communications capability it requires.

Summary of Recommendations

1. Collect data and build a data base which lists candidate earth stations and orbiting satellites.
2. Conduct "on-site" link testing at as many locations as feasible and for all marginal links.
3. Publish a report after all data have been collected and correlated and issue it to all earth stations. The report will indicate every combination of accessible transponder.
4. Identify and prioritize government emergency communications requirements.
5. Develop and write computer software to allow real-time, on-line reconstitution and reconfiguration of the satellite network.
6. Consider supplying a standard set of signal processing equipment for gateway earth stations to insure equipment compatibility.
7. Study the effects of a nuclear-charged atmosphere on propagation and communications equipment in greater depth.
8. Establish an on-going procedure for maintaining accurate information in the data base.

BIBLIOGRAPHY

Bell, Trudy E. "Technology '84: Communications." IEEE Spectrum, January 1984, p. 55.

Bellamy, John. Digital Telephony. New York, NY: John Wiley & Sons, 1982.

Bhargava, V. K.; Harcoun, D.; Matyas, R.; and Nuspl, P. Digital Communications by Satellite: Modulation, Multiple Access and Coding. New York, NY: John Wiley & Sons, 1981.

Bond, Fred E. Systematic Approach for Commercial Satellite Survivability, August 3, 1984. Los Angeles: The Aerospace Corporation.

"Book Targets Pentagon's Command, Control System," Boulder (Colorado) Daily Camera, May 17, 1985, p. 14B.

Braun, Walter H. "2^{o} Spacing: Its Impact on Domestic Satellite Systems." Satellite Communications, November 1981, p. 32.

Carter, Ashton B. "The Command and Control of Nuclear War." Scientific American, January 1985, pp. 32-39.

Commercial Satellite Communications Survivability Report, May 20, 1983 and Addendum, December 15, 1983. Prepared by the CSS Task Force Resource Enhancements Working Group.

Federal Communications Commission. "U.S. Domestic Satellites," undated information sheet.

Fthenakis, Emanuel. Manual of Satellite Communications. New York, NY: McGraw-Hill Book Co., 1984.

Gagliardi, Robert M. Satellite Communications. Belmont, CA: Lifetime Learning Publications, 1984.

GTE Satellite. "GSTAR Satellites Technical Specifications." GTE Satellite Corp., December 12, 1984.

GTE Spacenet. "Spacenet Satellites Technical Specifications." GTE Spacenet Corp., December 12, 1984.

Haddad, Hussain. Lecture notes from "Trends in Satellite Communications Systems," University of Colorado, Spring Semester, 1985.

Hammond World Atlas. Maplewood, NJ: Hammond, Inc., 1981.

Ippolito, Louis J. et al. Propagation Effects Handbook for Satellite Systems Design. NASA Reference Publication 1082(03), June 1983.

Kuller, W. G. and Hanifen, D. W. "Space System Survivability," Laser and Laser Systems Reliability, Proceedings of SPIE - The International Society for Optical Engineering, Vol. 328, January 28-29, 1982, pp. 72-81.

LaVean, Gilbert E. "Interoperability in Defense Communications." IEEE Transactions on Communications, Vol. COM-28, No. 9, September 1980, pp. 1445-1455.

Lewin, Leonard, ed. Telecommunications: An Interdisciplinary Test. Dedham, MA: Artech House, Inc., 1984.

Maley, S. W. Unpublished notes on modulation.

Martin, James. Communications Satellite Systems. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1978.

__________. Telecommunications and the Computer. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1976.

Morgan, Walter L. "RCA Satcom 14/12 GHz Satellites." Satellite Communications, Feburary 1984.

__________. "Satellite Notebook: SBS-1." Satellite Communications, May 1981.

RCA. "Ku-Band Satellite System." RCA American Communications, undated.

Raymond, H. G. and Kliger, J. "Demand Assignment Technique for Mixed User Services." AIAA 6th Communications Satellite Systems Conference, April 5-8, 1976, pp. 269-291.

Reagan, Ronald. Executive Order 12474, Assignment of National Security and Emergency Preparedness Telecommunications Functions, April 3, 1984.

Rudie, Norman J. Principles and Techniques of Radiation Hardening. North Hollywood, CA: Western Periodicals Company, 1980.

Silbermann, George F. H. National Security Agency representative to the National Communications System. Telephone interview, July 17, 1985.

Smith, Edwin. "Nuclear Effects on RF Propagation." Defense Electronics, October 1984, pp. 228-232.

Spilker, James J., Jr. Digital Communications by Satellite. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1977.

Tansini, Jonathon. "Are We Sitting Ducks in a Nuclear War?" Business Week, July 8, 1985, pp. 12-13.

Trobau, Robert (Staff engineer, American Satellite Corp.). Telephone conversation, April 15, 1985.

Turco, Richard P.; Toon, Owen B.; Ackerman, Thomas P.; Pollack, James B.; and Sagan, Carl. "The Climatic Effects of Nuclear War." Scientific American, August 1984, pp. 33-43.

Van Trees, Harry L., ed. Satellite Communications. New York, NY: IEEE Press, 1979.

Watson, P. A. and Soutter, C. J. "Dual Polarization Frequency Re-use in Satellite Communications Systems at 11 GHz." International Conference on Satellite Communication Systems Technology. London: Whitefriars Press Ltd., 1975, p. 297.

White, David (Staff technician, SBS TT&C Site, Castle Rock, Colorado). Telephone conversation, July 12, 1985.

END

FILMED

11-85

DTIC